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Theoretical investigation of using a direct contact dehumidifier in humidification–dehumidification desalination unit based on an open air cycle

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ABSTRACT

In the present work, a kind of direct contact dehumidification process used in humidification–dehumidification system is introduced instead of using the conventional indirect condensers. In the purposed system, air is dehumidified by spraying cold water into the hot and humid air stream. The freshwater production, efficiency and effects of various parameters including air flow rate, conditions of inlet cold and hot water and velocity and diameter of droplets on the performance of the system are investigated. Results showed that increasing initial velocity and diameter of water droplets decreases water production. Furthermore, it has been demonstrated that increasing the flow rate and temperature of hot water and reducing the flow rate and temperature of cold water will increase freshwater production and the efficiency. It is found that increasing air flow rate has negative effect on production and energy consumption of the system. Direct contact dehumidifier has a good potential in desalination of seawater which can resolve many operational problems of indirect condensers like: corrosion, salt water leakage, and hydraulic pressure drop.

Keywords: Humidification; Dehumidification; Direct contact; Water spray; Desalination

1. Introduction

Because of population growth and restriction of freshwater resources in the world, desalination of brackish water and seawater is increasingly used in many countries in the world. Some common desalination methods like multi-stage flash, multi-effect, and vapor compression are economic only for large capacity ranges of 100–100,000 m^3/day of desalination, but these technologies are expensive for small amounts of freshwater and also cannot be used in locations, such as islands or remote areas, where maintenance facilities and energy supply are restricted [1]. Furthermore, these technologies often require large amounts of energy that usually use oil and natural gas, which results in large CO_2 emission. Therefore, there is a strong interest in alternative energy sources, and in particular renewable energy sources, for desalination units. Production of freshwater using desalination technologies driven by the solar energy systems is thought to be a viable solution to the water scarcity at remote areas characterized by lack of potable water and abundant solar radiation.

Air humidification–dehumidification (HD) desalination is a suitable option for freshwater production when the demand is decentralized. Also, as HD

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system operates at low temperature, it is compatible with solar energy and total required thermal energy can be obtained from solar energy. Performance of the HD systems have been studied and improved by several researchers [2,3]. Goosen et al. [4] reviewed various layouts of the HD desalination systems as well as single- and multiple-effect solar desalination. Authors mentioned the fact that many of these units may be technically very efficient but may not be economic. However, increase in future demand of freshwater might make several of these processes viable for freshwater production. Alhallaj et al. [5] constructed a HD desalination unit in Basrah, south of Iraq. The unit had a capacity of $12\,\mathrm{L/d\,m^2}$ of solar collector surface. However, the pressure drop in the condenser and the humidifier was too high, increasing the electrical power consumption by the blower to a level that makes such a process uneconomical. Chafik [6] presented a new type of seawater desalination plant using solar energy. A dynamic simulation program has been developed to predict, optimize, and design solar desalination plants according to the new process. Narayan et al. [7] have been studied a detailed thermodynamic analysis in order to improve and optimize the performance of various HD cycles by way of a theoretical cycle analysis. A global optimization of HD process was developed by Soufari et al. [8]. Effects of different parameters were analyzed and a mathematical programming model was presented to optimize the process with different objective functions. Then the model was developed by adding the solar part and finally a low-cost design for HD desalination was obtained [9]. In the next step, a unit with capacity of 10 L per hour based on optimization results were constructed [10]. They use indirect condenser as dehumidifier that preheated the feed salt water.

Various types of heat exchangers have been used as dehumidifier in HD system. Dawoud et al. [11] have presented an overview on the possible cooling technologies of the condenser of a seawater greenhouse desalination technique via air HD. They suggested that evaporative cooling with surface seawater seems to be the most suitable cooling technology for the greenhouse condenser. Ettouney [12] evaluates several layouts for the HD tower, which includes the conventional humidification system combined with either one of the following units to condense the water vapor from the air: water condenser, membrane air-drying, vapor compressor, and lithium bromide absorption desorption. Analysis of these four configurations shows the need to determine the most efficient design and operating conditions that generate the minimum product cost. The utilization of direct contact heat exchangers as a condenser is studied in some studies. Klausner et al. [13] used a direct contact dehumidifier in combination with a shell and tube heat exchanger to provide enhanced condensation and improved heat recovery for the cycle. Also they evaluated using packed bed in direct contact humidification and dehumidification process [14,15]. They analyzed the evaporative heat and mass transfer for the packed bed and compared results with the experimental data [16]. Klausner et al. [17] developed theoretical model for transient heat and mass transfer during the evaporation and the condensation for the packed bed. Eslamimanesh and Hatamipour [18] investigated a HD process in which direct contact process was used for humidification and dehumidification operations. Zamen et al. [19] presented a novel system based on direct contact humidification and dehumidification on packed bed for freshwater production in greenhouse. They simulated and designed an integrated system with greenhouse that supply the required energy by solar absorber tubes that located in a sealing zone below the roof of the greenhouse. They evaluated the potential of the system in freshwater production during the year and concluded that the direct contact dehumidification on packed bed can be used instead of indirect condenser. It can solve many operational problems of indirect condenser and that can help commercialization of this technology.

Studies of previous investigations show that the condenser has been the main bottlenecks of freshwater production from seawater. Some studies suggested the using of direct contact condensation instead of indirect condensers. This study evaluates spraying freshwater into the air stream, as a direct contact dehumidifier in an open air HD unit in order to extract vapor from the humid air. In this way, water droplets in the dehumidifier are brought into direct contact with the hot and humid air and the heat and mass transfer will occur between the humid air and the water droplets. In this work, the performance of the system is evaluated through mathematical modeling of the system that presented in the next section.

2. Process description

The HD process that evaluated in this study is shown in Fig. 1. It consists of a horizontal channel, including humidifier and dehumidifier. In order to increase contact area between air and salt water in the humidifier, a kind of structural packing is used.

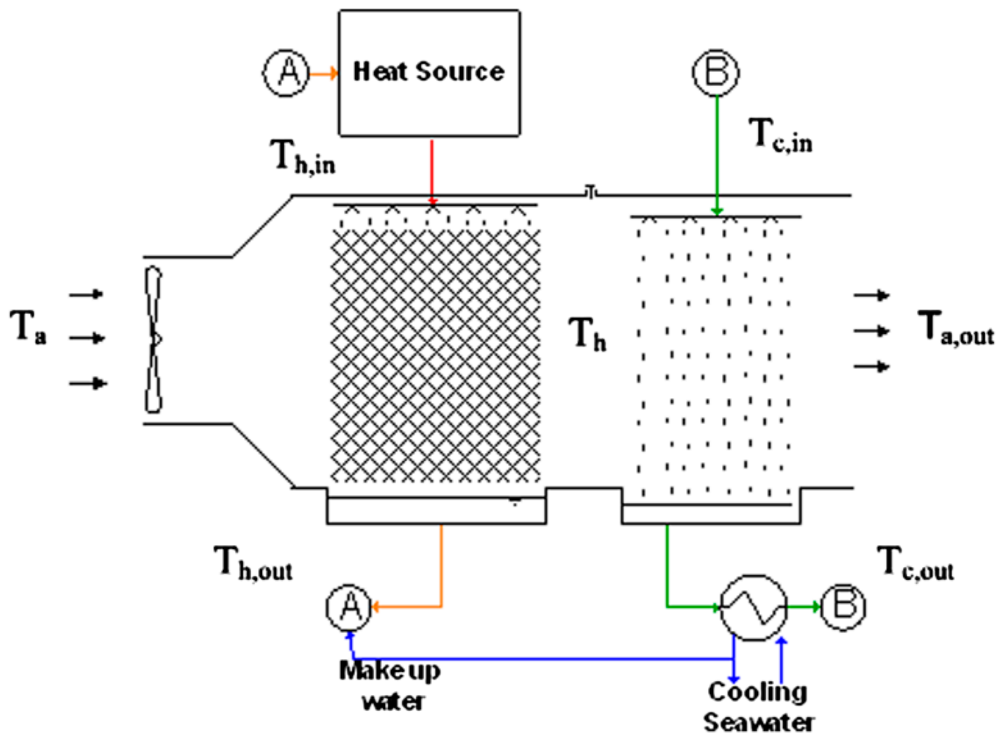

Fig. 1. Sketch of the HD unit with an opened air cycle and water heating.

In the humidifier, water which has been heated by an external heat source, like solar collector, distributed on top of the packing and air passes horizontally through that. The air temperature and humidity increase during passing the packing. Outlet water can be heated and recycled to the humidifier. Then the hot and humid air enters the dehumidifier.

As cited before, most investigations have used indirect contact heat exchangers to dehumidify air and often they have problems such as corrosion and high pressure drop. Direct contact dehumidifier can solve many operational problems of indirect condensers such as corrosion, salt water leakage, hydraulic pressure drop, etc. In this article, water spray as a kind of direct contact dehumidifier is used that can result in lower capital cost. Using freshwater spray system instead of packed bed dehumidifier will result in elimination of packed bed and required supporting structure.

The water spray nozzles are arranged in crossflow with the airstream. So, humid air is directly in contact with cold freshwater spraying as water droplets. The cold water droplets absorbs heat from the air and extra water vapor of air condenses and it is added to the cold water streams. Condenced vapor was collected as produced freshwater. Then the main part of this stream can be cooled with seawater in a heat exchanger and then recycled to the dehumidifier. A part of cooling seawater can be used as make-up water in the humidifier.

3. Modeling of the system

In order to evaluate the theoretical performance of direct contact humidification and dehumidification process, the mathematical analysis based on mass and energy balance equations is used to model this system. Some assumptions should be considered to simplify the analysis:

(1) The process is done under adiabatic conditions.
(2) System operates at constant atmospheric pressure of 101.33 kPa.
(3) Temperature and humidity of air/vapor mixture (T_g,ω) change only in the horizontal direction (in air flow direction).
(4) Water temperature and flow rate (T_L,L) change only in the vertical direction (water flow direction).

In previous studies [8–10], theoretical and experimental results of air humidification process onto a structural packing and air dehumidification by fin-tube condenser for a closed air loop, with counter flow streams, have been presented. Furthermore in recent study [19], humidification process with cross-flow streams of air and water has been developed. Also for dehumidification modeling, equations that is used by Nirooman and Amidpour [20] for humidification process through water spray is modified for dehumidification process.

In the humidifier, the direction of heat transfer and mass transfer is from water to air stream; and thus, air stream is heated and humidified and water temperature decreases. The basic concept and corresponding equations are as the same as those detailed in the previous study [19].

Based on the given assumptions, the humidification and dehumidification processes can be modeled. For this purpose, structural packing is divided into some smaller elements that are shown in Fig. 2. In each element, heat and mass balance equations can be written and solved. For the element number 1 in the humidifier, the properties of the inlet air and hot water are known. After solving the heat and mass balance equations for this element, outlet air conditions (T_g,ω) and outlet water conditions (T_L,L) will be determined that are the inlet data for solving the element number 2 and number $n+1$, respectively. Hence, equations can be consequently solved based on the numbering that is shown in Fig. 2. Finally, outlet conditions of the air and water streams from the humidifier are determined. The method of modeling dehumidification process is similar to modeling humidifier. Knowing hot and humid air properties that entered the dehumidifier and also cold freshwater temperature and flow rate, heat and mass transfer equations can be solved for the dehumidifier by using the method that will be explained later. Fig. 3 shows more details of heat and mass transfer in an element of humidifier whose direction is from water to air. If dv is the volume of each element and a_H will be the specific area of the structural packing, then the heat transfer area for each element is equal to ($a_H dv$).

If the hot water flow rate of the humidifier is equal to L_h, then the hot water flow rate of an element will be $L_{h,e}$ that depends on the number of elements in the air flow direction. Additionally, if the total dry air flow rate is equal to G, then the dry air flow rate for an element will be G_e which depends on the number of elements in the height of packing. In this fashion, mass balance for an element yields a result:

$$L_{h,e} = G_e d\omega_{g,h} \tag{1}$$

Energy balance of air and water side is, respectively, as follows:

$$G_e C_{g,h} dT_{g,h} = h_{g,h}(a_H dv_h)(T_{i,h} - T_{g,h}) \tag{2}$$

$$L_h C_{L,h} dT_{L,h} = h_{L,e}(a_H dv_h)(T_{L,h} - T_{i,h}) \tag{3}$$

On the air side, mass transfer balance yields:

$$G_e d\omega_{g,h} = k_{g,h}(a_{m,h} dv_h)(\omega_{i,h} - \omega_{g,h}) \tag{4}$$

Finally, heat balance for the interface will be as follows:

$$h_{g,h}(a_H dv_h)(T_{i,h} - T_{g,h}) + L_{v,h} k_{g,h}(a_{m,h} dv_h)(\omega_{i,h} - \omega_{g,h}) = h_{L,h}(a_H dv_h)(T_{L,h} - T_{i,h}) \tag{5}$$

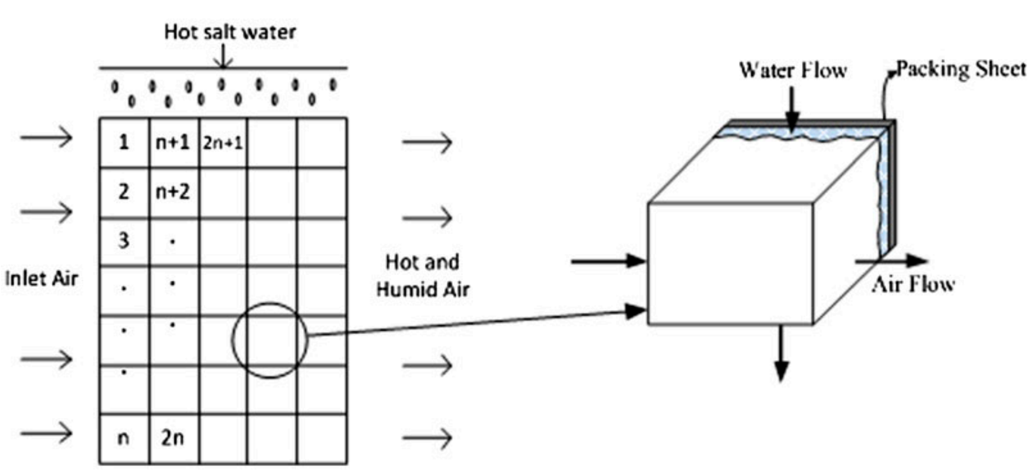

Fig. 2. Grid elements of packing in humidifier.

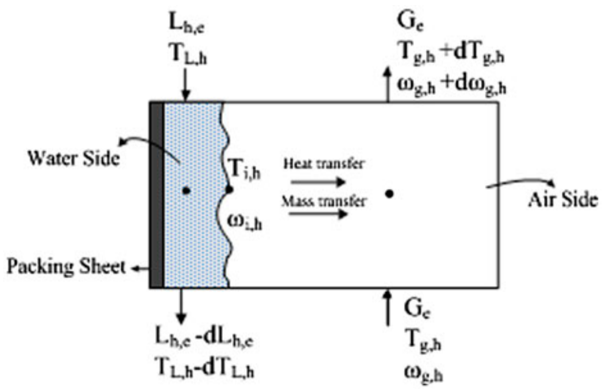

Fig. 3. One element of humidifier and heat and mass transfer direction.

In the dehumidifier, water droplets interact with the air, heat and mass transfer occurred between droplets interface and humid air. Since water temperature is less than the air, the heat and mass transfer direction is from air to water. Both of the latent heat of condensation and the sensible heat transfer from air to the water phase. The temperature and humidity ratio of the air in outlet of the dehumidifier depends on inlet air and water conditions.

To calculate the temperature and humidity ratio of the dehumidifier outlet, the dehumidifier is divided into smaller elements. The basic concept of solving method is similar to the humidifier. In each element, there are some water droplets as shown in Fig. 4(a). Direction of heat and mass transfer is also depicted in Fig. 4(b). It is assumed that all droplets have the same behavior in each element. Also, the droplets leave the nozzles in the same initial velocity and diameter.

For any water droplet in each element, mass balance can be written as [20]:

$$\frac{dL_d}{dy} = \frac{-\rho_g A_s h_m (\omega_i - \omega)}{U_y} \tag{6}$$

Water temperature in control volume is increased according the following equation [20].

$$\frac{dT_d}{dy} = \frac{6\left[h(T_g - T_d) - L_v h_m \rho_g (w_i - w)\right]}{D_d \rho_d U_y Cp_d} - \frac{3h_d}{Cp_d D_d}\frac{dD_d}{dy} \tag{7}$$

where h and h_m are heat and mass transfer coefficients and could be calculated by Kachhwaha et al. [21]:

$$Nu = \frac{h_g D}{\lambda_g} = 2.0 + 0.6\mathrm{Re}_d^{0.5}\,\mathrm{Pr}^{1/3} \tag{8}$$

$$Sh = \frac{h_m D}{D} = 2 + 0.6\mathrm{Re}^{0.5} Sc^{0.33} \tag{9}$$

The momentum conservation equation for the droplet is given below [22]:

$$\frac{d(L_d U_y)}{dy} = \frac{L_d g}{U_y}\left(\frac{\rho_g}{\rho_d} - 1\right) - C_D\left(\frac{\pi D_d{}^2}{4}\right)\left(\frac{\rho_g W^2}{2}\right)\left(\frac{U_y}{W}\right) \tag{10}$$

Reynolds number is calculated based on the velocity of drops relative air that is expressed as [21]:

$$\mathrm{Re}_d = \frac{\rho_g W D}{\mu_g} \tag{11}$$

where W is the relative velocity vector and C_D is the drag coefficient which can be calculated as [21]:

$$\begin{aligned} C_D &= \frac{18.5}{\mathrm{Re_d}^{3/5}},\ 1.9169 \le \mathrm{Re_d} < 508.3917 \\ C_D &= 0.44,\ \mathrm{Re_d} \ge 508.3917 \end{aligned} \tag{12}$$

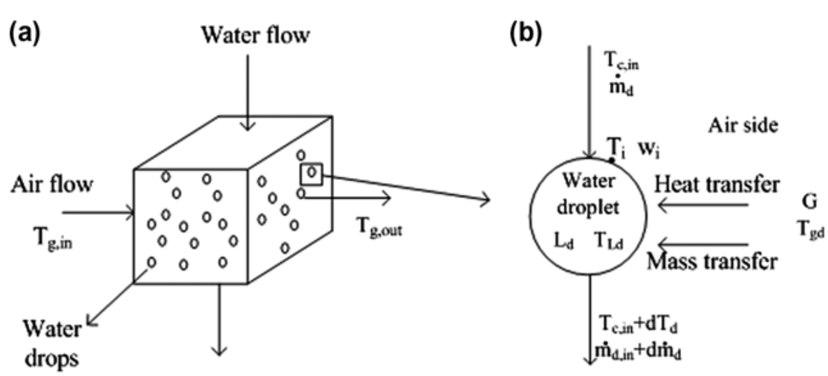

Fig. 4. (a) One element of dehumidifier and (b) heat and mass transfer direction.

The number of the water droplets could be calculated by Eq. (13). It is assumed that distribution of droplets in the condenser is uniform.

$$N = \frac{6L_c}{\pi d^3 \rho_L} \tag{13}$$

Energy should be kept in balance between the droplet and the air, so the equation in condenser can be expresses as:

$$L_c Cp_{c,L}(T_{c,out} - T_{c,in}) = G(H_{g,in} - H_{g,out}) \tag{14}$$

Enthalpy of wet air per unit mass can be expressed as [23]:

$$H_g = 1.005T + \omega(2500 + 1.88T) \tag{15}$$

To obtain the temperature of the air in the dehumidifier outlet, Eqs. (6)–(14) should be solved simultaneously. The air temperature strongly depends on the diameter, velocity, and temperature of water droplets.

Then, freshwater production is calculated by following equation:

$$\dot{m}_{pw} = G(\omega_2 - \omega_1) \tag{16}$$

4. Results and discussion

Performance of the direct contact humidifier and spray water dehumidifier in HD desalination process is analyzed by using mathematical modeling. Results are presented in terms of variations in air flow rate, the inlet cold and hot water temperatures, the initial water droplet velocity and diameter which are the main effective parameters that markedly affect the performance of the process. In this work, both the humidifier and the dehumidifier sections are channels with 1×1 m cross-section area and 0.5 m length (air travel distance) for each section.

4.1. Effect of the velocity and diameter of water droplet on the water production

Fig. 5 shows the variation of water production with the equivalent diameter of the water droplets for different initial velocities. It is clear that the increment of the equivalent diameter adversely affects the heat and mass transfer, regarding the decrement in the contact area that decreases the amount of water production. Moreover, increasing in initial velocity of droplets results in reducing the retention time of the droplets in the dehumidifier, hence, it declines the heat and mass transfer. As mentioned, decrease in heat and mass transfer will result in reducing water production. So, the initial velocity and the diameter of water droplets should be considered as one of the most important design parameters and also should be chosen carefully, otherwise it reduces the amount of water production. To produce smaller droplets, nozzles with smaller outlet diameter and higher pressure water are used. Then the higher water pumping power is needed which lead to more costs.

4.2. Effect of the inlet hot/cold water temperature on the water production

Fig. 6 shows the effect of the inlet hot and cold water temperature on the freshwater production. In higher inlet hot water temperature, humidity and temperature of outlet air from the humidifier will increase, which enhance the heat and mass transfer efficiency in the dehumidifier. It is because of increasing driving force for heat and mass transfer between humid air and cold water droplets. Also, this figure demonstrates that the amount of water production decreases by escalating of $T_{c,in}$. As $T_{c,in}$ decreases, the difference between the temperature of cold water and the warm air increases that lead to higher mass and heat transfer and results in more water production. On the other hand, the driving potential for the mass transfer, as water droplets pass through the air inside the dehumidifier, is the difference between the saturated vapor pressure at the surface of the droplets

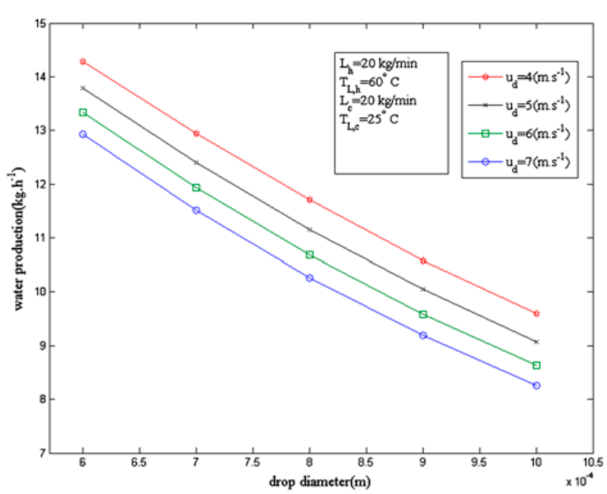

Fig. 5. Effect of inlet water droplets diameter to dehumidifier on fresh water production.

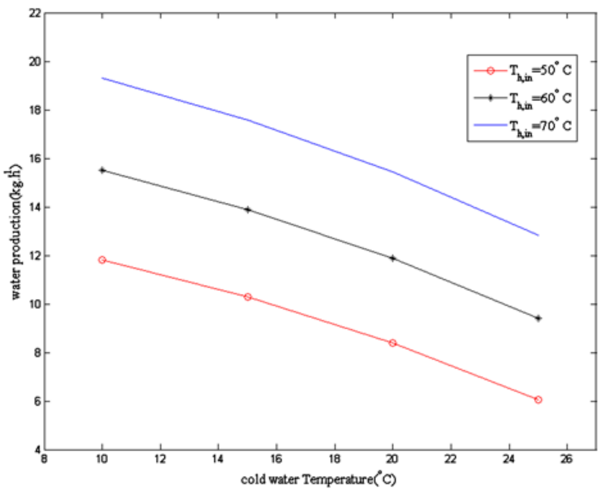

Fig. 6. Effect of inlet water temperature to dehumidifier on fresh water production.

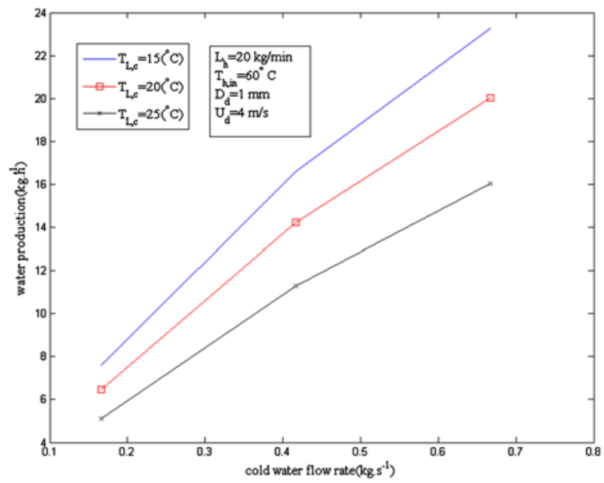

Fig. 7. Effect of inlet water flow rate to dehumidifier on fresh water production.

and the bulk air stream pressure. So, increasing the inlet cold water will result in decrease of the pressure difference, which means driving potential for mass transfer reduces and causes less water production. So, using deep seawater, that is often less than 15℃, will have great effect on productivity of the system.

4.3. Effect of inlet cold water flow rate

The influence of the inlet cold water flow rate on the water production for different cold water temperature is represented in Fig. 7. It is shown that by growth in cold water flow rate, the amount of water production would enhance. Increasing the cold water flow rate would increase the number of water droplets in the air, so the overall heat transfer area between water and air will be promoted, and the water production will be promoted correspondingly. It should be noted that the gradient of water production decreases with increasing of the cold water flow rate.

4.4. Effect of air mass flow rate

Fig. 8 illustrates the effect of the air mass flow rate on the evaporation rate in the humidifier. As shown in this figure, by increasing the air flow rate the amount of evaporation in the humidifier will increase to some extent due to increase of mass transfer coefficient. On the other hand, increasing G could decline the residence time of air flow contact with hot water which can explain constant variation of evaporation in higher air flow rates. Effect of air mass flow rate on condensation rate is shown in Fig. 9. With an increase of G, although total amount of vapors in the air flow that enters to the dehumidifier increases, the air would leave the humidifier with lower temperature which affects the performance of the dehumidifier adversely. In other hand, the growth of G would increase velocity, heat and mass transfer coefficients in the dehumidifier which could improve water production, but it could not compensate the reduction of driving force and temperature in the humidifier. Therefore, in general, increasing the air mass flow rate decreases the water production of the system.

When L_h/G increases, the air will be heated to a higher temperature which leads to higher vapor absorption capability of air. Therefore, increasing of temperature and driving force in the humidifier

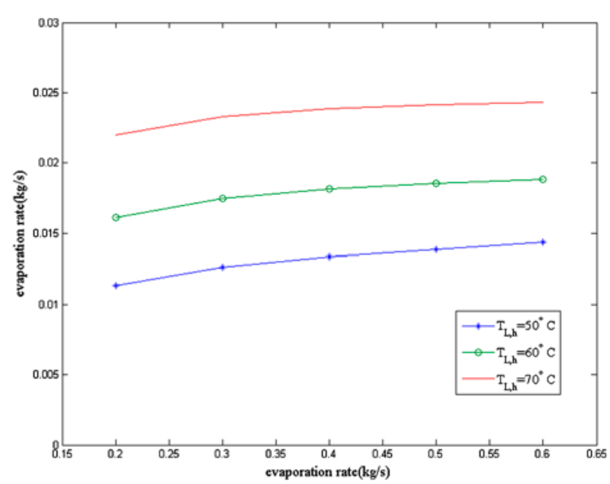

Fig. 8. Evaporation rate vs. air flow rate.

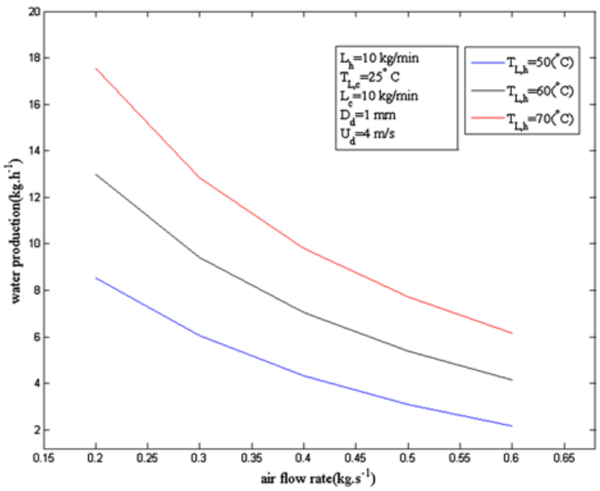

Fig. 9. Condensation rate vs. air flow rate.

would be the reason for the increasing of water production, as Fig. 10 demonstrates. Optimum water production can reach to a value of 25 kg h^{-1} for $T_{\mathrm{h,in}} =$ 70˚C from a minimum value of 5 kg h^{-1}. Furthermore, the impact of the hot water temperature on the optimum water production in higher L_{h}/G is more than in lower L_{h}/G.

In the HD process, the outlet water in the humidifier needs to be heated up to the temperature required for the humidifier entrance in a heat exchanger. The heat rate needed for heating of water with a constant flow rate is given as:

$$\dot{Q}_{\mathrm{heating}} = L_h c_p (T_{\mathrm{h,out}} - T_{\mathrm{h,in}}) \tag{17}$$

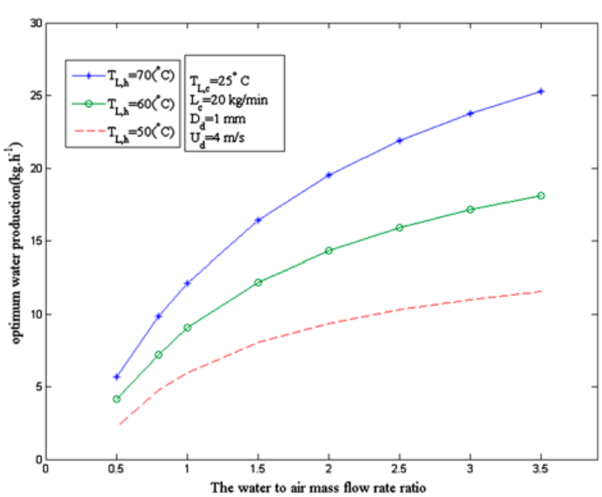

Fig. 10. Optimum water production vs. L_{h}/G.

Also, the outlet water in the dehumidifier needs to be cooled down to the temperature of the inlet water as Eq. (18):

$$\dot{Q}_{\mathrm{cooling}} = L_{\mathrm{c}} c_{\mathrm{p}} (T_{\mathrm{c,out}} - T_{\mathrm{c,in}}) \tag{18}$$

The specific energy for both heating and cooling rate is expressed as:

$$\text{Specific energy} = \frac{\dot{Q}}{\dot{m}_{\mathrm{pw}}} \tag{19}$$

Variation of the specific heating energy consumption with the air flow rate for some specific values of hot water temperature is depicted in Fig. 11. The specific energy consumption is varied approximately between 3 and 16 kWh kg^{-1} which for lower hot water temperature increases. Increasing air flow rate enhances the evaporation rate that causes decrease of the outlet water temperature and increase in the heating energy consumption. On the other hand, increasing G reduces freshwater production. Therefore, lower mass flow rate of air decreases the specific energy consumption and enhances the performance of the system (productivity and energy consumption).

Fig. 12 shows that the specific cooling energy has similar trend toward increasing the air flow rate. It is about 0.7–0.8 kWh kg^{-1} for various condition of inlet water which has less variation with the change of the air flow rate compared to the specific heating energy. Furthermore, the specific heating energy is averagely 4–20 times more than the specific cooling energy. However, increasing in G decreases cooling energy, reduction of water production is more than that which causes their ratio increase. By escalating $T_{\mathrm{c,w}}$ driving force in the system will decrease which causes the temperature in the process diminish. So, despite

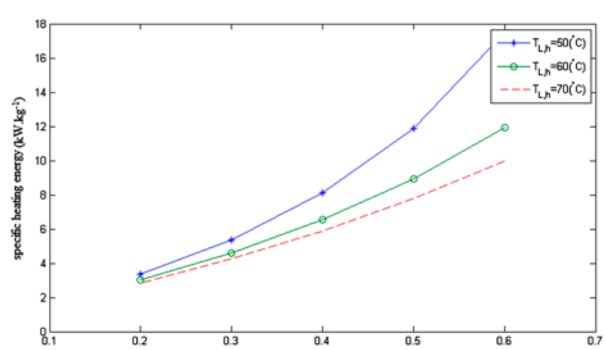

Fig. 11. Specific heating energy vs. air flow rate.

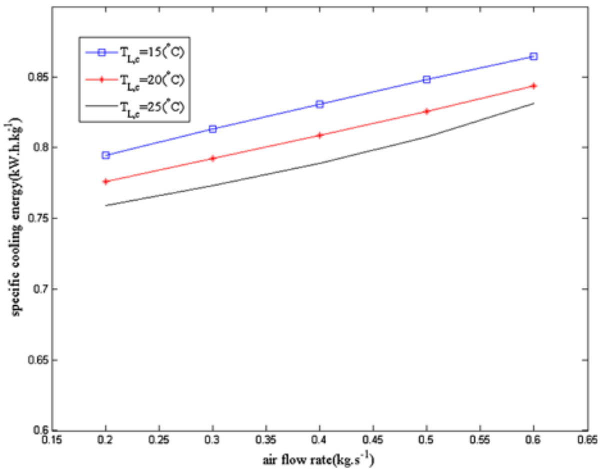

Fig. 12. Specific cooling energy vs. air flow rate.

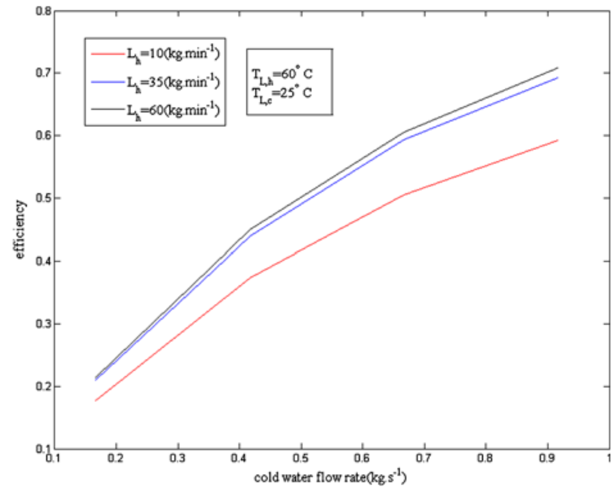

Fig. 13. Efficiency vs. cold water flow rate.

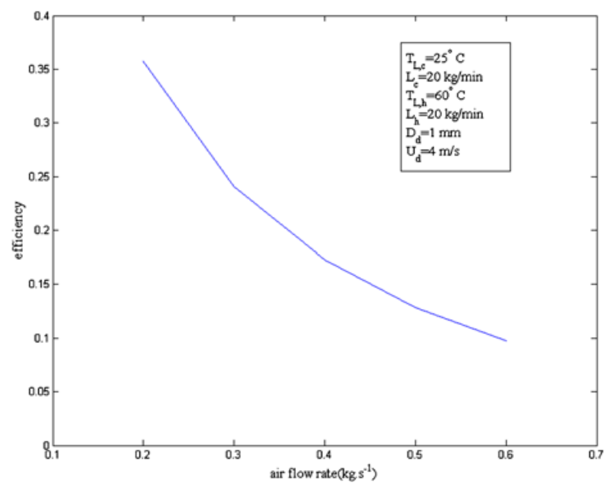

Fig. 14. Efficiency vs. air mass flow rate.

decreasing freshwater production, the cooling energy will reduce, which causes a decrease in the specific cooling energy. Investigation on the trend of specific energy demonstrates that increasing in G does not benefit the performance of the system. So, the air flow rate is an effective parameter which should be controlled and lower amount of that has positive effect on performance of the system.

To evaluate the efficiency of the HD process, a new parameter is defined as the ratio of the condensation rate to the evaporation rate which indicates the amount of freshwater production compared to the amount of vapors available in the air flow, as following equation:

$$\eta = \frac{\dot{m}_{\mathrm{pw}}}{\dot{m}_{\mathrm{e}}} \tag{20}$$

Considering Fig. 13, it can be seen that escalating of cold water flow rate would increase efficiency, because of increasing in condensation rate. Also, rising of hot water flow rate increases the efficiency, because of increasing the driving forces in the humidifier which improve condensation rate. Furthermore, in higher $\dot{m}_{\mathrm{c,L}}$ and L_{h}, the effect of cold and hot water decreases as a result of remaining constant driving forces. The efficiency could be increased from 20 to 70%, by changing $\dot{m}_{\mathrm{c,w}}$ from 0.2 to 0.9 kg s^{-1}. Moreover, for higher hot water flow rates, efficiency is not affected by the hot water flow rate heavily. The variation of the efficiency with the air mass flow rate is depicted in Fig. 14. As it is clear, the efficiency declines dramatically by the growth of the air mass flow rate. The efficiency decreases about 70% by changing of G from 0.2 to 0.6 kg s^{-1} which expresses the negative effect of the growth of the air mass flow rate on the efficiency.

It also can be seen that water production in the introduced model is about 20–25% less than water production of the model proposed by Zamen et al. [19] which used packed bed as the direct contact dehumidifier. Although, reduction of the pressure drop and elimination of packed bed, which can result in reduction of capital cost, can compensate this reduction in water production.

5. Conclusion

In this study, the performance of HD desalination system based on direct contact heat and mass transfer process has been investigated. In the dehumidifier, water droplets are sprayed into the air flow due to dehumidify hot and humid air. In this way, some disadvantages of using indirect contact heat exchangers such as corrosion, salt water leakage, hydraulic pressure drop, etc. will be eliminated. The following conclusion can be drawn from the analyses.

- It is shown that increasing in diameter and velocity of water droplets has negative effect on freshwater production. Therefore, the type of the nozzle should be selected carefully to produce droplets with appropriate initial diameters and velocities.
- The amount of water production increases significantly by increasing cold water flow rate.
- The distillate output of the system declines by increasing of the cold water inlet temperature and rises by escalating of the hot water inlet temperature.
- For higher values of L_h/G, optimum water production increases.
- Specific heating energies rise heavily by the growth of the air flow rate, while the specific cooling energy does not change significantly.
- The efficiency that is defined as the ratio of the condensation rate to the evaporation rate can be more than 10% that increases up to 70% with increasing hot and water flow rate. It is a great success in HD desalination units that can be obtained with purposed system.

The analysis and results indicate that by utilization of spray water dehumidifier, freshwater production could reach to a maximum value of $25\,\mathrm{kg\,h^{-1}}$, which means it would be a feasible design. So, an economical study on water spray would be worthwhile.

Nomenclature

A — area
a_H — specific area of heat transfer (m^2/m^3)
a_m — specific area of mass transfer (m^2/m^3)
C — specific heat (J/kg K)
G — air flow rate (kg/s)
H — enthalpy ($J/kg_{dry\ air}$)
h — convection heat transfer coeficient (W/m^2K)
h_m — mass transfer coefficient
k_g — mass transfer coefficient of air/water mixture (kg/m^2s)
L — mass flow rate of water (kg/s)
L_v — evaporation latent heat (J/kg)
M — mass flow rate (kg/s)
T — temperature
U — drop velocity
v — volume

Greek symbols

ω — humidity ratio
H — efficiency
ρ — density [$kg\,m^{-3}$]

Subscripts

C — cold
D — drop
D — dehumidifier
E — element
g — gas
H — humidifier
i — interface
In — inlet
L — liquid
Out — outlet
S — surface
v — vapor

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