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Performance of bubble column humidification-dehumidification (HDH) desalination system

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ABSTRACT

Bubble column humidification and dehumidification (HDH) system is considered one of the promising and new techniques for enhancing the performance of the HDH desalination systems. In this paper, we experimentally examine the performance of a bubble column water and air heated HDH systems. The effect of water column height in the humidifier, water temperature, and air temperature and flow rate on gain output ratio (GOR), production and effectiveness are investigated and discussed. Results show that the system can produce 0.6 L/h freshwater and GOR can reach 0.95. At low temperatures, increasing airflow rate leads to an increase in the production at a high rate than the rate of increase in heat input. Therefore, GOR slightly increases at a higher airflow rate. Furthermore, GOR increases with increasing water temperature in the dehumidifier because the decrease in input energy needed to cool water in the dehumidifier has more impact than the decrease in the production.

Keywords: HDH; Bubble column; Experiments; Desalination; Performance

1. Introduction

Due to rapid growth in population, agricultural and industrial activities, there has been a rapid increase in the freshwater demand. To meet this demand, there is extensive research on water desalination. Nevertheless, there is a great demand for small-to-medium scale stand-alone water desalination systems to produce fresh water in remote areas [1]. Humidification-dehumidification (HDH) technology is a promising method for water desalination due to its simple design and compatibility with low energy requirements. HDH is a thermal cycle technology that imitates the natural rain cycle. The cycle consists of three main components: a humidifier, a dehumidifier, and a heater. There are several configurations for HDH, where most of them have the potential for high energy recovery [2,3].

HDH water desalination system is comprised of humidification, heating and dehumidification processes. The humidification process can be achieved by several methods. These methods include spray tower, wetted-wall tower, packed-bed tower, and the bubble column [4] to load air, the carrier gas, with water vapor. The bubble column humidifier is a groundbreaking method for humidification where air enters the humidifier generating bubbles in the water column, these bubbles can be distributed uniformly around the cross-section of the humidifier using a perforated plate or a sparger. As air bubbles move through the hot water column, heat and mass transfer take place simultaneously. The higher rate of heat and mass transfer in bubble columns have made them attractive to be used as multiphase reactors in metallurgical, biomedical, and chemical processes [5]. However, the use of bubble column humidifiers in HDH

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water desalination systems received limited attention. The investigations reported in the open literature include experimental work that investigates the single-stage or multi-stage bubble column humidifier performance [6–15], carrier gas selection [16] and integration of the humidifier with mechanical vapor compression (MVC) [17], or a shell and tube dehumidifier [7,18]. On the other hand, bubble column or direct contact dehumidifiers have been analyzed experimentally [19–27] and theoretically [25,28–30].

El-Agouz and Abugderah [6] analyzed the performance of a bubble column humidification process under varying operation parameters. Performance criteria were established as humidification efficiency defined as the ratio between the differences of actual to maximum humidity. Bubbles are generated by pressurized air supply through 32 holes of 10 mm diameter, each being submerged into heated water. They reported an increase in humidification efficiency with column temperature and air temperature and velocity. In an extension to their work, El-Agouz [7] studied the complete HDH system along with the bubble column humidifier. In this system, an air compressor equipped with shell and tube heat exchangers (as dehumidifier) was used. Perforations in the humidifier were made on 15 mm (dia.) pipe with 44 holes on its surface. The superficial velocity of 2.8 m/s is maintained with a water temperature of 50°C–90°C and water column height in the range of 20–60 cm. It was concluded that freshwater productivity increases with air flow rate and water temperature while the effect of water column height is negligible. Govindan et al. [8] studied experimentally both single and multistage bubble humidifiers. They indicated that using a multistage humidifier may result in an effectiveness of about 89%. Munteshari [9] and Al-Qutub and Munteshari [10] also studied experimentally the performance of a multistage bubble column humidifier. They considered the effect of air superficial velocity, mass flow rate ratio, watergate height and sparger profile on the unit performance. They achieved a maximum effectiveness of 88.9% for a three-stage bubble column humidifier.

Ghazal et al. [11] studied a bubble column humidifier using a flat-plate solar collector in which water is heated whereas air enters through holes of a perforated pipe at its bottom. The perforated pipe is 60 cm long and has a diameter of 1.3 cm while the hole diameter is 2 mm. Results indicated that the relative humidity of outlet air is almost 100% and the humidification efficiency is more than 90%. It was concluded that the bubble column humidifier is an effective way for the humidification process.

Abd-ur-Rehman and Al-Sulaiman [12,13] investigated the operating parameters for the performance of a multistage stepped bubble column humidifier. Heat and mass transfer rates increase by increasing residence time in the humidifier. Therefore, air is heated and humidified in the humidifier. Zhang et al. [14] reported that air leaving the bubble column humidifier has a relative humidity of 100%. They reported that increasing the airflow rate increases both humidification and pressure drop through the holes. Humidification also increases by increasing air and water temperatures. Khalil et al. [15] recommended a hole diameter of 1 mm for the air injection in bubble column humidifiers and indicated that bubble column humidifiers outperforms conventional packed bed unit.

Taseidifar et al. [16] investigated the performance of the carrier gas in the humidifier. They reported that helium has the highest efficiency compared to air, Ar and CO_2. Rajaseenivasan et al. [17] studied the performance of an HDH system, using a bubble column humidifier and a shell and tube dehumidifier. The maximum gain output ratio (GOR) of the system was 3.3, whereas the maximum productivity was 23.92 kg/m^{2}d.

Vlachogiannis et al. [18] experimentally studied the effect of bubble generation along with the MVC system. Their experimental setup includes an evaporation chamber as a humidifier, air bubbles rise through a porous plate placed at the bottom within the water column in the humidifier. Humidified air enters a compressor where it is compressed and heated. Airflow passes through a distributor to 25 vertical tubes where it is allowed to condense at the internal side and returns to the humidifier; thus, forming a closed-loop air cycle. They reported that saline water's temperature has a direct effect on productivity. Increasing saline water temperature increases the distillate quantity and reduces energy consumption in the compressor. Letzel et al. [19] measured the gas holdup of nitrogen–water system in a bubble column of 15 cm diameter and 1.22 m height operated at a pressure range of 1–13 bar. Results showed that increasing pressure increases gas holdup. This is due to the increase of the gas density with pressure, which decreases the bubble diameter.

On the other hand, dehumidification is one of the major processes in the HDH water desalination system. The effectiveness of the dehumidifier controls the performance of the HDH system, due to the large area required to condense water vapor from the air. Therefore, dehumidification still needs further investigation [20]. Bubble column dehumidifier has formerly been shown to reduce dehumidifier size by an order of magnitude [21].

Khedr [22] reported that finned heat exchangers widely used as dehumidifiers in HDH systems have limited thermal performance due to low energy recovery. He proved that direct contact dehumidification is more effective with minimum condensation area. When bubbles move through the water column, heat and mass transfer occurs simultaneously. The higher rate of heat and mass transfer in bubble columns have made them attractive to be used for freshwater production with minimal cost. Klausner [23] used a direct contact dehumidifier with a packed bed humidifier for freshwater production in a diffusion-driven desalination system. He compared the experimental values with the conventional design. The heat transfer coefficient was very low in the presence of non-condensable gases, up to an order of 100 W/m^{2}K.

Tow and Lienhard [24,25] performed modeling and experimental study on dehumidifier performance. In their experimental setup, a square dehumidifier area of 28 × 28 cm^2 and a height of 36 cm with a perforated plate at the bottom were considered. The effect of coil length inside the dehumidifier from 0.67 m to the largest coil of 3 m is investigated for coil flux and effectiveness of the bubble column unit. The airflow rate range of 1.4 to –2.8 L/s was considered at a constant surface temperature inside the column. The experiments showed that flux decreases with the increases in coil length unlike the effectiveness, which rapidly increases and becomes constant at higher values of length. The effectiveness decreases while the flux increases with increasing airflow rate.

Sharqawy and Liu [26,27] experimentally investigated the effect of pressure on the dehumidification process in a bubble column dehumidifier. Results show that increasing air velocity increases the unit's effectiveness and heat transfer rate. Though, increasing pressure decreases the effectiveness and heat transfer rate. Nevertheless, the column height in the dehumidifier has an insignificant effect on the effectiveness and heat transfer.

Barret and Dunn [28] studied the detailed mechanism for heat and mass transfer in the design of direct contact humidifiers and dehumidifiers using tray columns. His work is considered a pioneer work that focuses on the simultaneous heat and mass transfer equations within the dehumidifier.

He et al. [29,30] developed a mathematical model to investigate an HDH desalination system using a direct contact dehumidifier. Investigations show that the proposed system has a maximum GOR of 2.01. Moreover, they performed a cost analysis, and it was found that the highest water production of the HDH desalination system is not consistent with the lowest capital cost case.

Form the previous discussion, it has been noticed that the bubble column dehumidifier can reduce the dehumidifier size by an order of magnitude. However, most of the reported investigations in the open literature were investigating the performance of the humidifier and dehumidifier separately. Thus, more investigations are required to provide a better understanding of the performance of bubble column HDH. Furthermore, different HDH layouts using a bubble column unit have been significantly overlooked. Therefore, the objective of this paper is to fill this gap by critically examining the performance of both water heated and air heated bubble column HDH systems. In this regard, the effect of operating parameters is investigated and both systems are compared.

2. Experimental setup

The HDH system used consists of three stages: humidification, heating, and dehumidification. Bubbles column units are used for both HDH processes to increase the rate of heat and mass transfer between air and water, which would result in more effective evaporation and condensation.

The schematic diagram of the bubble column HDH system is shown in Fig. 1. For the water heater system, air is flowing from a compressor through hot seawater in a bubble column humidifier where a perforated plate generates air bubbles. As air bubbles rise in the humidifier, air is heated and humidified. Warm humid air leaves the humidifier at the top. On the other hand, for the air heated system, air flows from a compressor to a cylindrical air heater, where its temperature is controlled using a thermostat. Then, hot air enters the humidifier from the bottom through the perforated plate where it is humidified and slightly cooled.

In the bubble column dehumidifier, humid air is injected through cold freshwater. The freshwater may be cooled by a heat exchange coil connected to a chiller to keep the water temperature in the dehumidifier low to improve the condensation of moist air. As humid air rises as bubbles, water vapor carried by the air condenses and increases the level of freshwater in the dehumidifier.

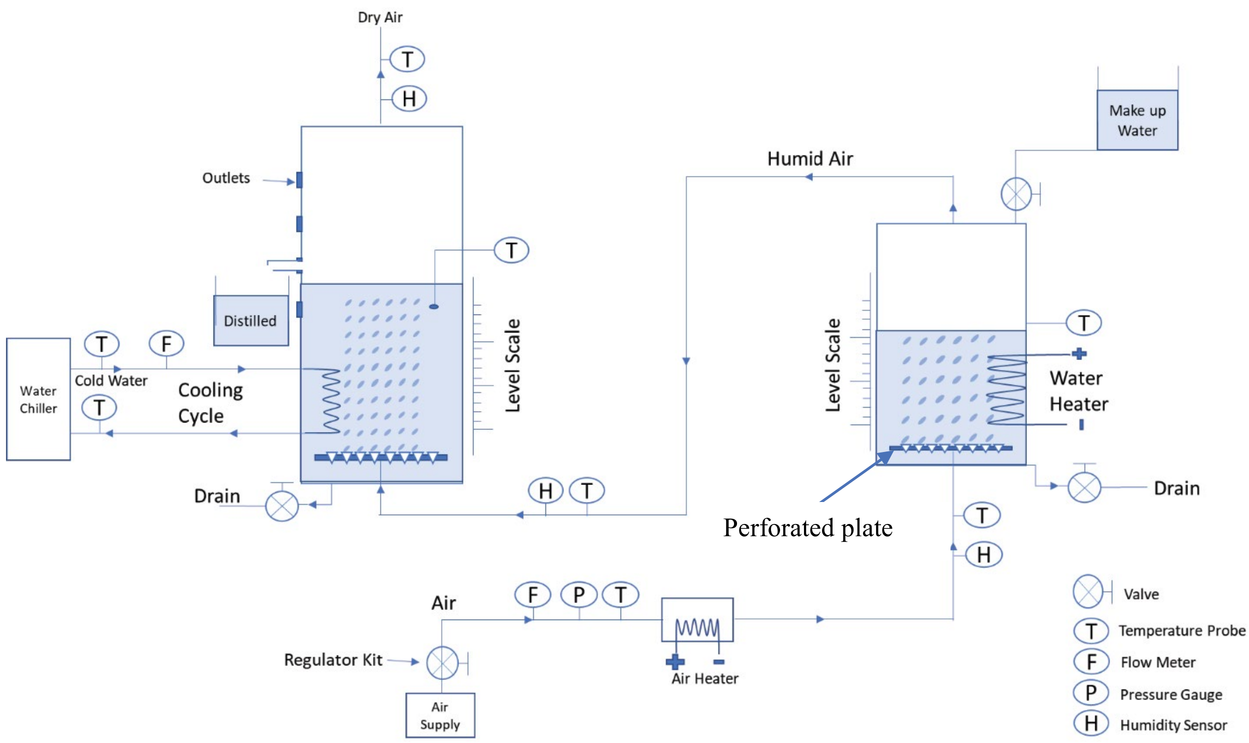

Fig. 1. Schematic of the bubble column HDH system.

The base and the top cover of the cylindrical column are sealed to prevent water or air leakage. Inside the unit, there is a water heater that is sufficient for raising the water temperature to the required set value. The water heater is controlled by a thermostat. On the bottom surface of the column, there is an air chamber to supply air into the water column of humidifier via a perforated plate with evenly distributed holes. The function of the plate is to provide a uniformly distributed bubble columns that allow the bubbles to transfer heat and mass more efficiently. At the top surface of the humidifier, two openings are made for controlling and measurements purpose, one is for a thermocouple probe to monitor the temperature of the humidifier, while the other one is used for the humidity sensor readings and the make-up water.

Humid air flows from the humidifier through the pipes to the dehumidifier. With the same working principles of the humidifier, humid air enters the dehumidifier where it is distributed uniformly inside the unit using a perforated plate to generate bubbles. Inside the dehumidifier, a cooling coil is placed for cooling the water, where cold water from the chiller circulates through a copper coil that is immersed in dehumidifier water. The top lid has four holes, two for the chiller cooling water (inlet, outlet), one for the humidity reading, and one is used for the temperature probe.

The humidifier used for the humidification of air is made of a plexiglass pipe with a diameter of 11.5 cm and a wall thickness of 6 mm the perforated plate has a diameter of 11.5 cm with 783 holes with a diameter of 2 mm and a pitch of 3.5 mm. The system is operated at atmospheric pressure, which is assumed to be 101.325 kPa.

In this test, air flows through the bubble column humidifier to carry some vapor as it flows through the perforated plate (for both air heated and water heated modes). Then, both the heater and chiller are turned on and the system it left to reach a steady state. Air passes through the dehumidifier to condense the moisture it carries. The condensate is collected as an increase in the water level in the dehumidifier. Recorded temperatures, humidity and flow rate values are used to assess the system performance.

For the water heater system, hot water temperature values tested are 65°C, 75°C, and 85°C. Whereas, airflow rate values used are 0.15 SCFM (standard ft^3/min), 0.25 SCFM, and 0.35 SCFM. Three water levels in humidifiers are considered, 4.5, 6, and 7.5 cm, respectively whereas water level in a dehumidifier is kept constant at 8 cm. Coldwater temperature in the dehumidifier varies from 10°C to 22°C.

On the other hand, for the air heated system, tested air temperature values are 110°C, 120°C, and 130°C. Three different flow rates of air are considered 1.0, 1.5, and 1.75 SCFM. Three water levels inside the humidifier are considered; 1, 1.5, and 2 cm. All thermocouples used are of *K*-type with 0.1°C resolution and ±0.5°C accuracy.

2.1. Uncertainty analysis

The uncertainty is evaluated in the results that are calculated based on experimental observations. Temperature sensors at different locations, flowmeter, and hygrometer are used to measure the operating parameters. The water level in the columns is measured directly by a ruler attached to the outside surface of bubble columns. It is required to measure the effect of these values on system performance parameters, distillate, effectiveness, and GOR.

Standard estimation of uncertainty in measurement is performed through instrument accuracies by the following equation [31,32].

$$U = \frac{a}{\sqrt{3}} \tag{1}$$

The uncertainties associated with the experimental facilities are shown in below Table 1.

Moreover, the engineering equation solver helps to determine the indirect uncertainty on the calculated values. For air heated cycle flow meter of 0.5–4.5 SCFM was used while for the case of water heated cycle it was 0.1 to 1.2 SCFM. The results of indirect uncertainty on calculated variables are shown in tabulated form as follows in Table 2.

2.2. Performance analysis

The performance of the bubble column HDH is evaluated through calculating the GOR, specific energy consumptions (SEC), the effectiveness of humidifier and dehumidifier. GOR is defined as the ratio of the latent heat of vaporization of produced freshwater to the amount of energy supplied to the process. Whereas, SEC is defined as the energy consumed to produce one kilogram of freshwater. The input energy is divided into heating load and cooling load. The heating load is the energy used to heat the water or the air in the humidifier, while, the cooling load represents the energy used to maintain the temperature in the dehumidifier (chiller load).

Table 1
Detailed description of instruments

Property	Instrument	Range	Accuracy	Standard uncertainty
Temperature	Digital thermocouple RDXL 12SD, *K*-type	–100°C to 1,300°C	±0.5°C	0.2886°C
Air flow rate	FL50000 Omega Flow meters	0.5 to 4.5 SCFM & 0.1 to 1.2 SCFM	(±5% FS), ±0.225 SCFM & ±0.06 SCFM	0.1299 SCFM & 0.0346 SCFM
Relative humidity	RH318 Hygro thermometer	0% to 100% RH	±2.0% RH	1.1547% RH

Table 2
Indirect uncertainty on calculated results

Parameter	Indirect uncertainty					
	Air heated cycle			Water heated cycle		
	1 SCFM	1.5 SCFM	1.75 SCFM	0.15 SCFM	0.25 SCFM	0.35 SCFM
GOR	±0.0011	±0.0017	±0.0028	±0.07459	±0.06067	±0.06387
Humidifier effectiveness	±0.0076	±0.0074	±0.0080	±0.01252	±0.01274	±0.01277
Dehumidifier effectiveness	±0.0277	±0.02337	±0.02262	±0.01161	±0.0182	±0.01204
Total heat input	±0.0742	±0.0742	±0.0748	±0.07425	±0.07425	±0.07425
Specific energy consumption	–	–	–	±0.731	±0.727	±0.698

The heating load is calculated based on the airflow rate and its temperature difference across the heating section, whereas in the case of water heating, we measure the input electric power of the heater. On the other hand, the chiller load is calculated based on the flow rate and temperature difference across the coil in the cooling cycle as shown in Fig. 1.

$$\text{GOR} = \frac{\dot{m}_d h_{\text{fg}}}{\dot{Q}_{\text{in}}} \tag{2}$$

$$\text{SEC} = \frac{\dot{Q}_{\text{in}}}{\dot{m}_d} \tag{3}$$

$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{heating}} + \dot{Q}_{\text{cooling}} \tag{4}$$

$$Q_{\text{heating}} = \dot{m}_{\text{air}} C_{\text{pair}} \left(T_{\text{air},o} - T_{\text{ambient}}\right)\left(\text{air heated}\right) \tag{4a}$$

$$Q_{\text{cooling}} = \dot{m}_{\text{chiller}} C_{\text{pwater}} \left(T_{\text{wo}} - T_{\text{wi}}\right) \tag{4b}$$

where $T_{\text{air},o}$ is the air temperature at the exit of air heater, $T_{w,i}$ and T_{wo} represent the water temperature at the inlet and exit of the chiller, respectively.

To evaluate the performance of the HDH system, enthalpy is a better measure than temperature because humidifier and dehumidifier are heat and mass exchangers and due to the non-linearity of the saturated air enthalpy-temperature curve. Thus, to study the effect of different parameters, expressions for the effectiveness are given in Eqs. (3) and (4). Effectiveness is the ratio of the actual heat transfer rate to the maximum possible heat transfer rate.

$$\varepsilon_H = \frac{h_{\text{air,out}} - h_{\text{air,in}}}{h_{\text{air,out,ideal}} - h_{\text{air,in}}} \tag{5}$$

$$\varepsilon_{\text{Dh}} = \frac{h_{\text{air,out}} - h_{\text{air,in}}}{h_{\text{air,out,ideal}} - h_{\text{air,in}}} \tag{6}$$

3. Results and discussion

The performance of water-heated and air-heated bubble column HDH systems is investigated. In this regard, the impacts of airflow rate, humidifier water level, and temperature, and air temperature on the system performance are measured. Results are presented in terms of system productivity, humidifier and dehumidifier effectiveness and GOR, as performance indicators. The effect of cooling the dehumidifier is studied against the no-cooling situation, and energy analysis is performed.

3.1. Effects of airflow rate and humidifier water level

3.1.1. Water heated HDH system

The influence of water level in humidifier and airflow rate on the system productivity, input energy, GOR, humidifier and dehumidifier effectiveness and air relative humidity for the water heater system are shown in Figs. 2 and 3. The water level in a humidifier is varied from 4.5 to 7.5 cm at a constant hot water temperature of 65°C, whereas water level at dehumidifier is fixed at 8 cm and temperature of 10°C. Readings are taken once the steady-state conditions are reached. Although increasing the airflow rate decreases air relative humidity since more air is passed within a fixed quantity of hot water, distillate production and input energy increases with increasing airflow rate (Figs. 2a and b). It implies that higher quantities of air passing per unit time are exposed to hot water and would accordingly be loaded with more water vapor. The input energy increases since a larger volume of the air requires more heating energy to keep the water at a fixed temperature. Fig. 2c shows the effect of increasing airflow rate on the system GOR. It is important, however to state that increasing the airflow rate leads to an increase in the production at a high rate compared with the rate of increase in heat input. Therefore, GOR slightly increases at a higher airflow rate as shown in Fig. 2c. The figure also shows the effect of water level on the performance parameters. Decreasing water the level in humidifier increases the amount of water evaporated, hence it increases production. However, it also increases the input heat significantly, which eventually reduces the GOR. It is important to state that GOR is low due to the absence of energy recovery in this system. Most of the energy used is consumed in water cooling the dehumidifier to control its water temperature.

On the other hand, humidifier and dehumidifier effectiveness increase with increasing airflow rate (Figs. 3a and b) since air is loaded with more moisture and its enthalpy

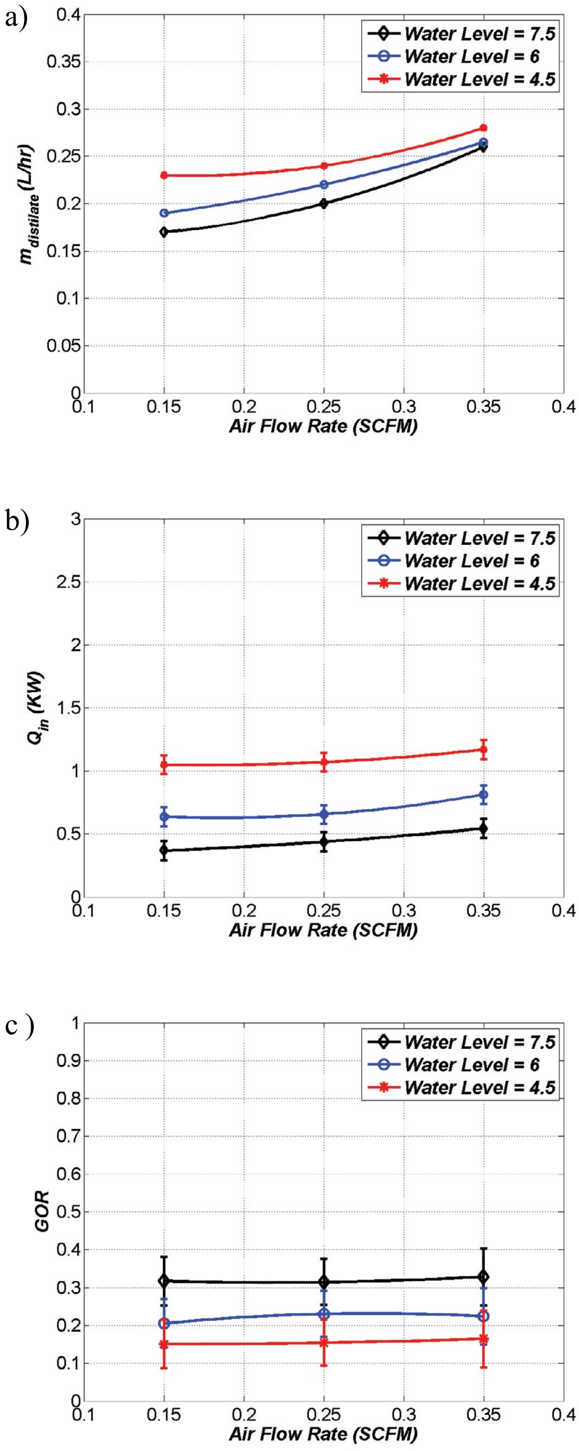

Fig. 2. Effect of air flowrate on (a) production, (b) energy required, and (c) GOR at different water levels in the humidifier-water heated system at T_w = 65°C, T_c = 10°C, and H_{wd} = 8 cm.

increases as it leaves the humidifier due to higher air temperature and humidity. Nevertheless, higher enthalpy of the air leaving the humidifier and flowing into the dehumidifier leads to better condensation of water vapor in the dehumidifier due to higher heat and mass transfer motive forces that

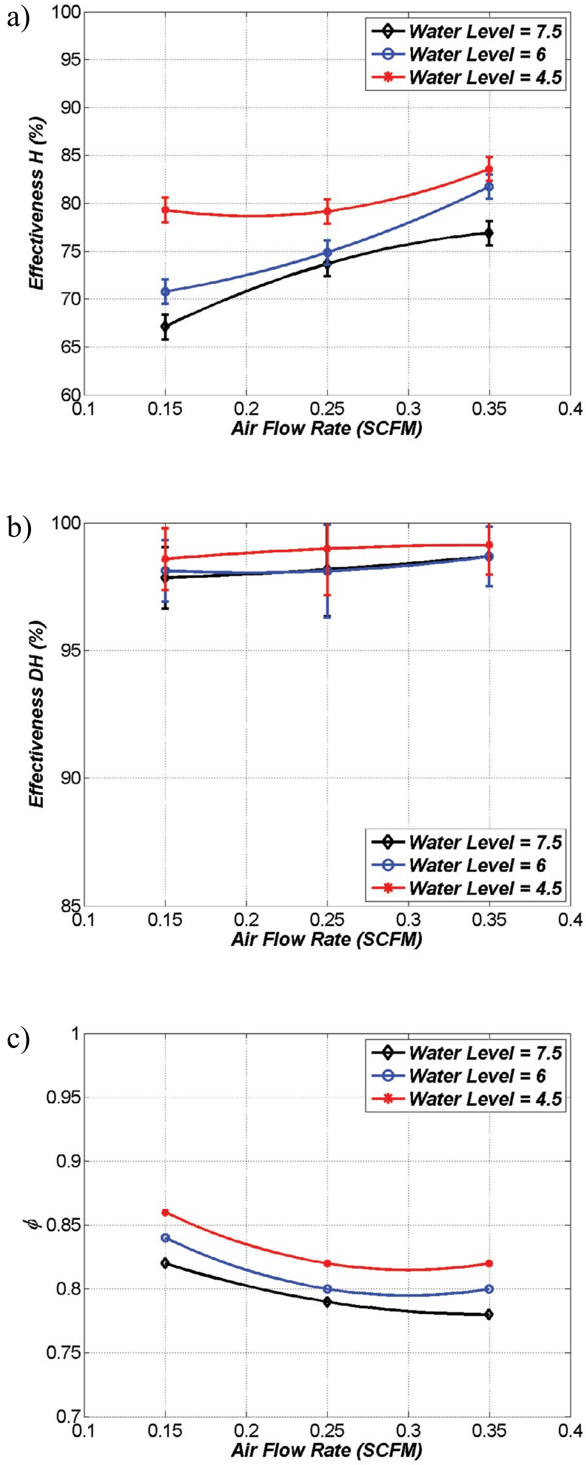

Fig. 3. Effect of airflow rate on (a) humidifier effectiveness, (b) dehumidifier effectiveness, and (c) relative humidity at different water levels in the humidifier for water heated system at T_w = 65°C, T_c = 10°C, H_{wd} = 8 cm.

lead to effective cooling that eventually leads to higher dehumidifier effectiveness. The decrease in the relative humidity with increasing airflow rate is attributed to more air is passing through a fixed water quantity, which limits air ability to absorb more water vapor. Moreover, the water level in humidifier has an impact on effectiveness. Decreasing water the level increases the amount of water evaporated since that increases the mass and heat transfer coefficients as it is more turbulent. Therefore, the effectiveness of humidifier increases.

3.1.2. Air-heated HDH system

The effects of water level in the humidifier and airflow rate on the performance of air heated bubble column HDH are shown in Figs. 4 and 5. Air temperature was kept at a constant value of 120°C (using an electric heater with thermostat) and the level of water inside humidifier is varied as 1, 1.5, and 2 cm for every set value of airflow rate. The water level inside the dehumidifier is kept at 6 cm. The readings are taken once the steady-state conditions are reached. Fig. 4a shows that water production increases proportionally with increasing airflow rate. This means evaporation or humidification of air is strongly influenced by the airflow rate. Also, the variation of humidifier water level has a noticeable effect on the distillate product. Lower water levels inside the humidifier are the favorable condition for higher distillate quantity. In case of air heated cycle, the air stream is hot and accordingly it is humidified and cooled in the humidifier. The higher flow rate of air is favored, while smaller water quantity in a humidifier (lower level) is favorable to avoid substantial air cooling. The distillate is higher (around 0.30 L/h) when the saline water level in humidifier is 1 cm. It is noticed that the energy required for cooling is more than the energy required to heat air because of the high mass flow rate of cooling water and its specific capacity. Therefore, the energy from the chiller is dominant in the total heat input. Hence, the total energy is almost constant with an airflow rate. GOR increases with increasing airflow rate and decreasing humidifier water level as shown in 4c. The effectiveness of the humidifier in air heated bubble column HDH is greater than the water heated bubble column HDH. Please note that for air-heated bubble column HDH, we maintain a lower water level in the humidifier to avoid substantial air cooling if the volume of colder water is large. This is because the warm humid air that leaves the humidifier is to be condensed in the dehumidifier. Unlike the water heated system, the total energy is almost constant with airflow rate for air heated cycle. The temperature of the air, after the heater, is kept constant at 120°C with flow rate increases. Therefore, the rate of input energy required to heat air depends significantly on the mass flow rate of incoming air. For the energy required by the chiller, it is smaller for the air heated system compared with the water heater system. This is due to the air temperature after the humidifier in the air heated system is lower than its corresponding value of water heated system. The highest GOR that can be achieved from the air heated system is 0.12 at a flow rate of 1.75 SCFM at a water level of 1 cm which is low compared to water heated cycle.

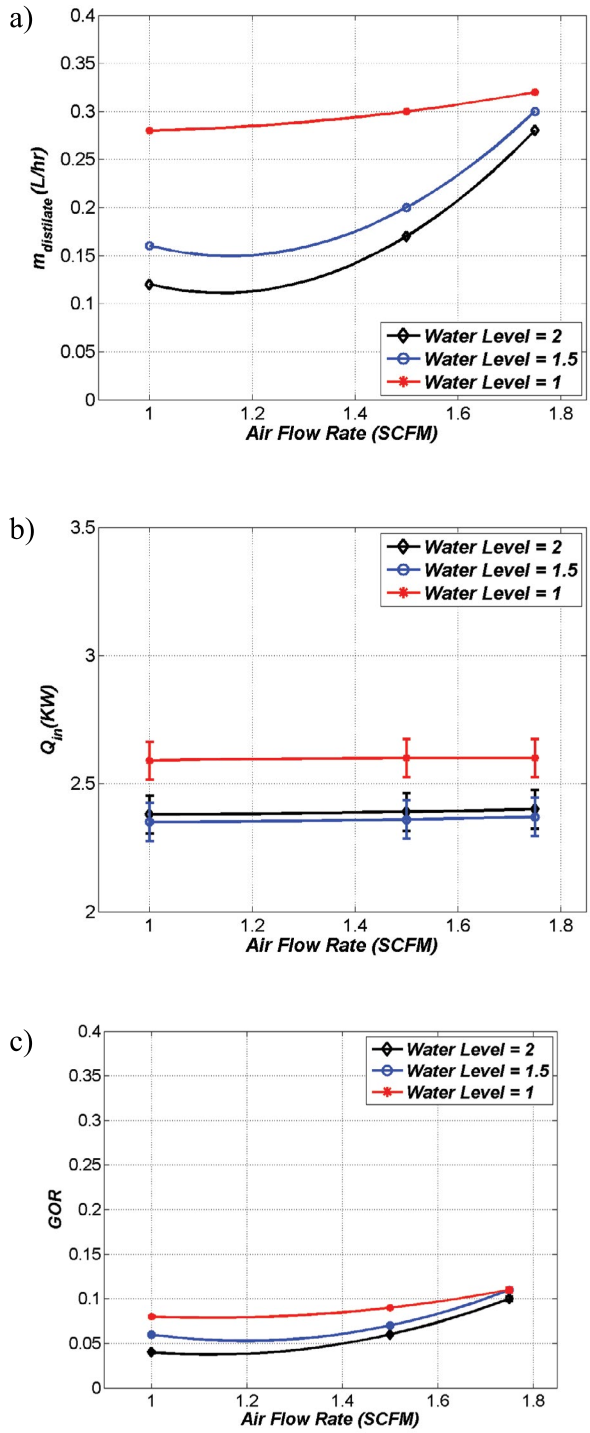

Fig. 4. Effect of airflow rate on (a) distillate, (b) Q_{in}, and (c) GOR at different water levels in a humidifier in the air heated system at air temperature of 120°C coolant temperature 15°C, and water level at dehumidifier was 6 cm.

3.2. Effect of water temperature in the humidifier of water heated system

Water temperature in the humidifier is one of the important factors that affect the performance in the water heated bubble column HDH. Thus, the performance of the bubble column HDH is analyzed while considering the effect of humidifier water temperature. For water heated systems, air is heated and humidified through its direct contact with hot water. This section investigates the effect of water

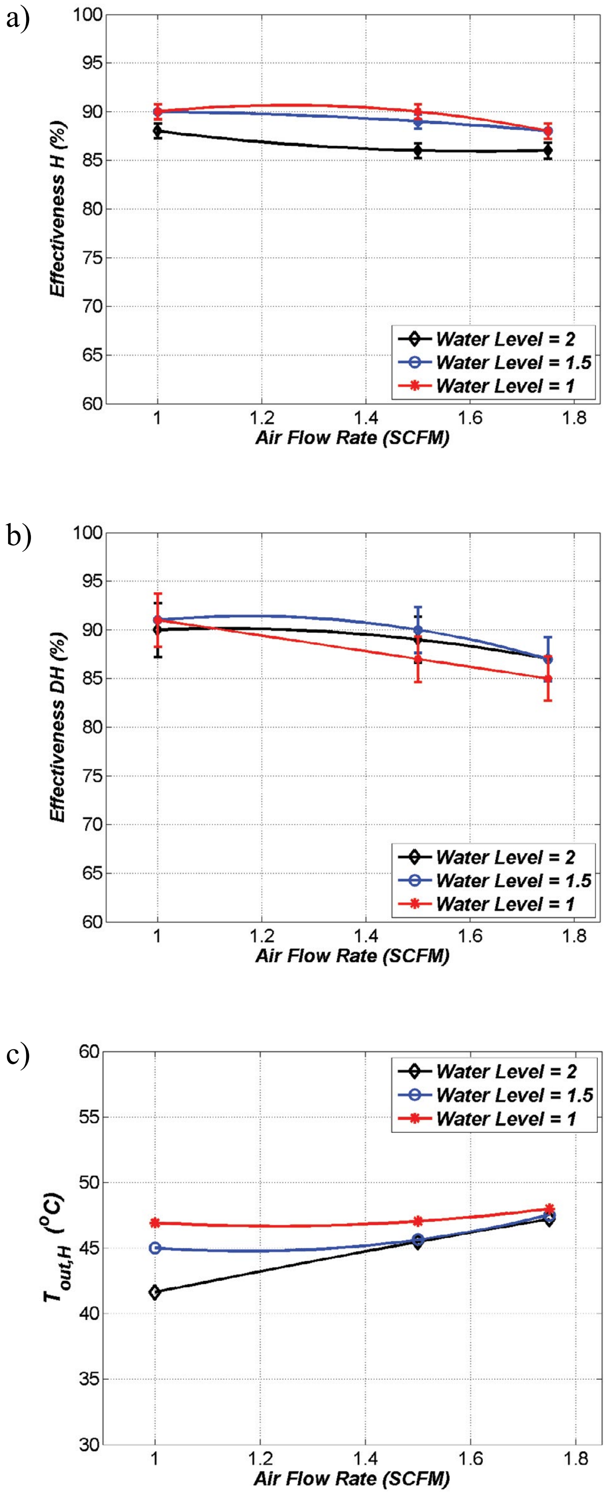

Fig. 5. Effect of airflow rate on (a) humidifier effectiveness, (b) dehumidifier effectiveness, and (c) $T_{out,}$ humidifier, at different water levels in a humidifier for the air heated system at an air temperature of 120°C coolant temperature 15°C, and water level at dehumidifier of 6 cm.

temperature in humidifier on production, input energy, GOR, humidifier effectiveness, dehumidifier effectiveness and relative humidity at a constant coolant temperature of 10°C as shown in Figs. 6 and 7. The water column height was maintained at 7.5 cm in the humidifier and 8 cm in the dehumidifier. Relative humidity increases with humidifier water temperature resulting in an increase in the distilled production as well as heat input, as shown in Figs. 6a and b, because air can absorb more moisture when its temperature increases. Increasing water temperature would lead to higher air temperature as it leaves the humidifier, which increases production. However, it increases the required input heat at a rate that is higher than the distilled production rate. Therefore, GOR decreases with water temperature, as shown in Fig. 6c.

Increasing water temperature in the humidifier in a water heated HDH system increases the humidifier effectiveness as shown in Fig. 7a, because of the increase in air temperature and humidity ratio, leading to higher enthalpy of the air stream leaving the humidifier compared to the air inlet condition. The high enthalpy stream enters the dehumidifier that condenses the water vapor carried by the air effectively due to low water temperature inside the tubes providing a better opportunity for condensation of water vapor on the tubes outer surface as shown in Fig. 7b.

3.3. Effects of air temperature and flow rate in humidifier of air-heated system

The effects of air temperature and airflow rate to the humidifier in the air-heated system on the performance are presented in Fig. 8. The high temperature of incoming air results in higher amounts of distillate productivity since air captures more water vapor at a higher temperature. A distillate rate of about 0.36 L/h was achieved at an air temperature of 130°C. This can be explained by the effects of the relative humidity of the air that decreases with the increase in air temperature. Increasing the temperature allows the air to hold a higher amount of water at that temperature, which in turn increases the humidification of air leaving the humidifier. The higher temperature difference between air inlet to the dehumidifier and the temperature of the water column in the dehumidifier results in better condensation and thus leads to an increase in the productivity and GOR as shown in Figs. 8a and c.

Figs. 9a–c shows the effect of air temperature on the humidifier and dehumidifier effectiveness, and the air relative humidity (Fig. 9c). Higher humidifier effectiveness is corresponding to the low-side of air temperature and flow rate. At an air temperature of 130°C, the values of effectiveness are on average 86%. On the contrary, when the air temperature is around 110°C the effectiveness of the humidifier bubble column is nearly 91% and 91% for a dehumidifier. This is believed to be because higher air temperature results in higher enthalpy difference between actual and ideal enthalpy of air leaving the humidifier. A similar result is shown for the dehumidifier effectiveness that is lower at cases where higher air temperatures are used. Higher temperatures are corresponding to lower values of relative humidity as shown in Fig. 9c since the increase of

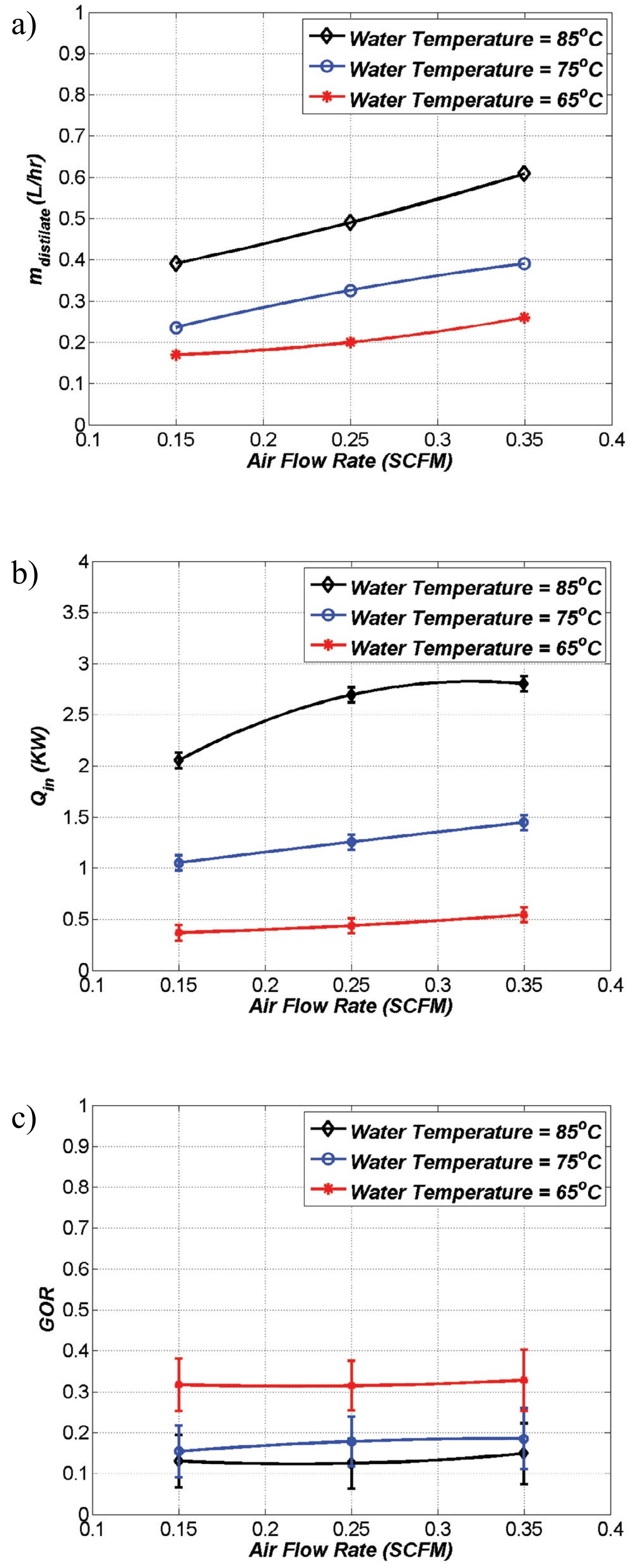

Fig. 6. Effect of water temperature in humidifier on (a) distillate, (b) Q_{in}, and (c) GOR in the water heated system at water level in a humidifier of 7.5 cm coolant temperature 10°C, and water level in dehumidifier = 8 cm.

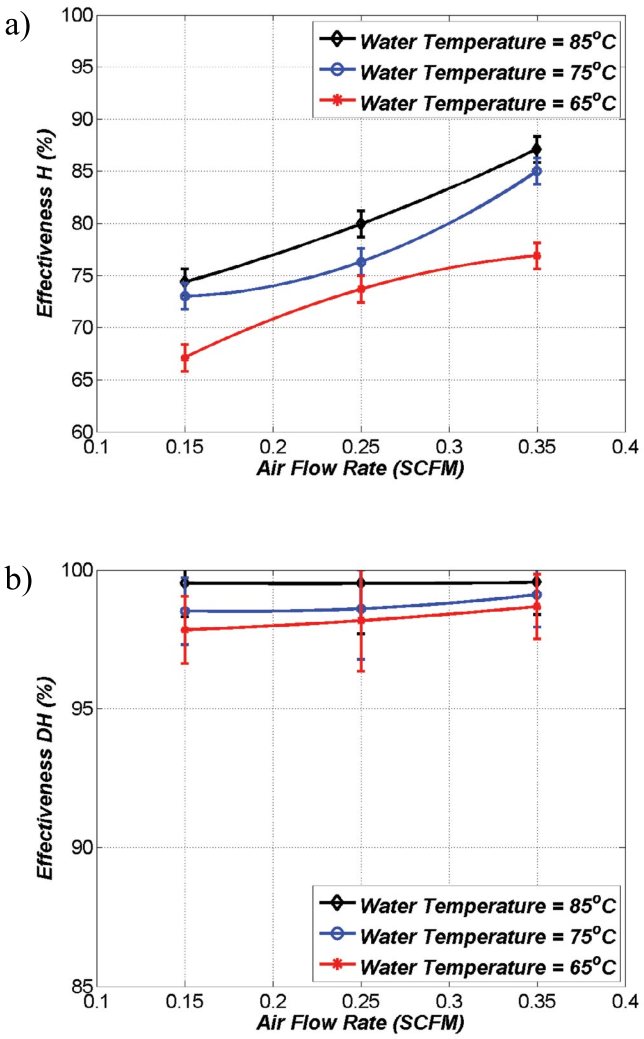

Fig. 7. Effect of water temperature in humidifier on (a) humidifier effectiveness and (b) dehumidifier effectiveness, in the water heated system at water level in a humidifier of 7.5 cm coolant temperature 10°C, and water level in dehumidifier = 8 cm.

temperature corresponds to lower relative humidity; if the humidity ratio is either constant or changes insignificantly.

3.4. Effect of water cooling in the dehumidifier of water heated system

Energy input for the system includes energy for heating water in the humidifier and the energy needed for cooling freshwater in the dehumidifier to maintain low water temperature in the dehumidifier for effective condensation. It is observed that cooling energy represents the majority of energy consumption as shown in Fig. 10. Thus, the effect of water temperature on the dehumidifier is investigated. The water column height is maintained at 7.5 cm in the humidifier and 8 cm in the dehumidifier of the water heater system. Inside the dehumidifier, a heat exchanger is placed for cooling the water, where cold water from a chiller circulates through a copper coil that is located within the dehumidifier

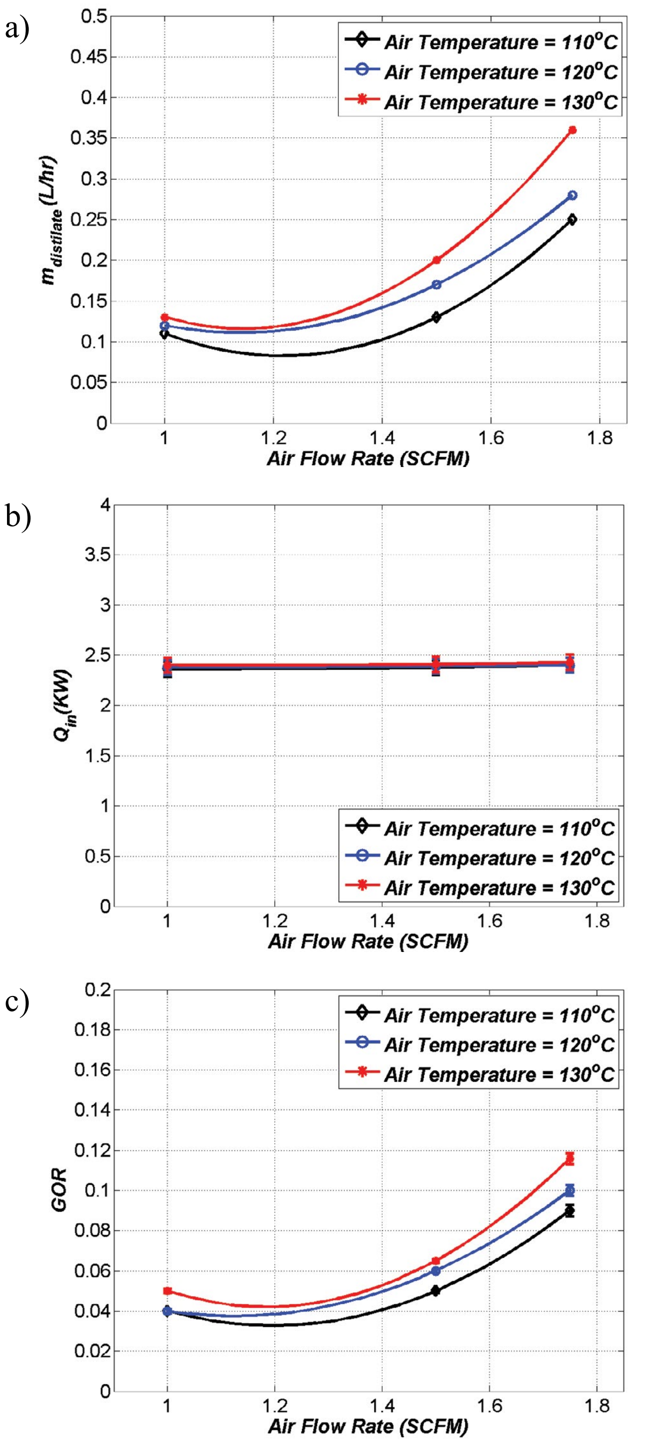

Fig. 8. Effect of airflow rate and air temperature in humidifier on (a) productivity, (b) heat input, and (c) GOR in the air heated system at water level in a humidifier of 2 cm coolant temperature 15°C, and water level in dehumidifier = 6 cm.

water column. The first set of experiments is conducted at water temperature in a dehumidifier of 10°C. In the second set of experiments, water temperature in a dehumidifier is maintained at 25°C, where water at ambient temperature circulates through the cooling copper coil without cooling.

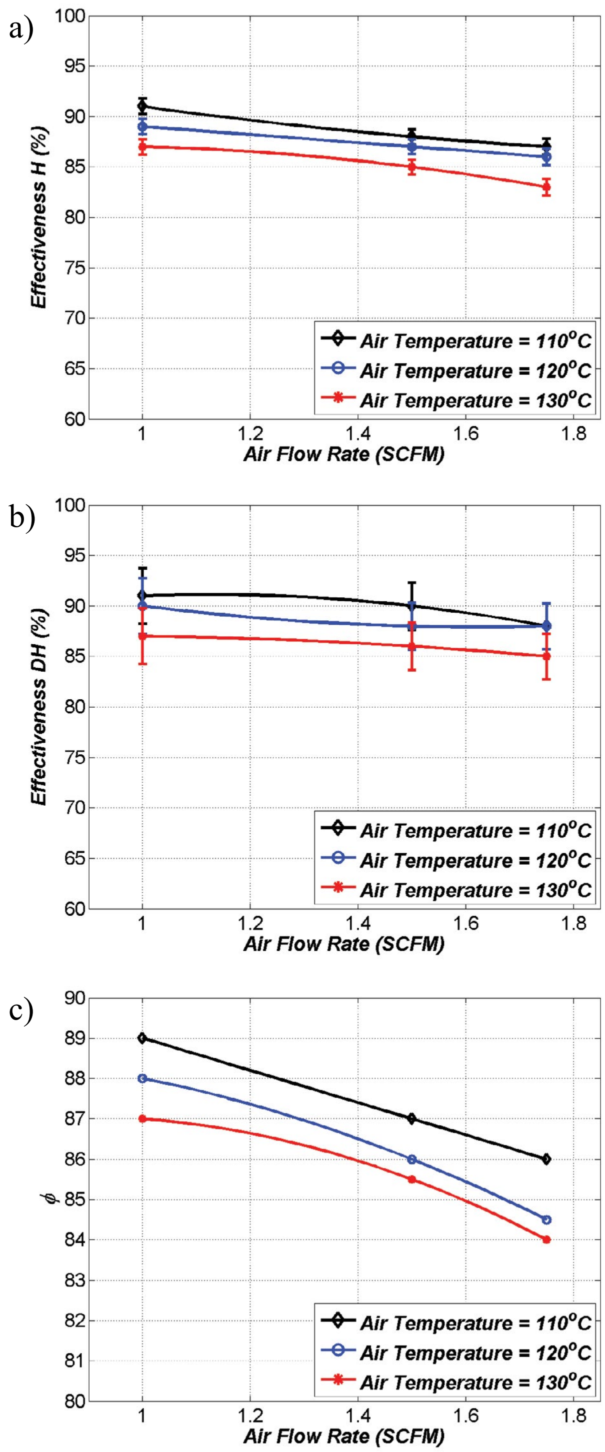

Fig. 9. Effect of air flow rate and air temperature in humidifier on (a) humidifier effectiveness, (b) dehumidifier effectiveness, and (c) relative humidity in the air heated system at water level in a humidifier of 2 cm coolant temperature 15°C, and water level in dehumidifier = 6 cm.

The results are illustrated in Fig. 11. The production decreases with increasing dehumidifier water temperature. This is because the air outlet temperature is directly related to water temperature such that it decreases the rate of condensation whenever the temperature difference between air and water decreases. However, GOR increases with the increasing water temperature in the dehumidifier because of the significant decrease in input energy needed to achieve the cooling effect. It turns out that this energy-saving is so significant that it has more impact on GOR improvement than decreasing the production.

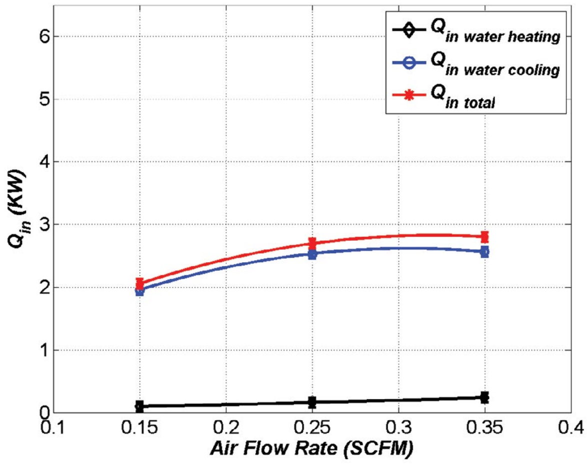

Fig. 10. Effect of airflow rate on heat input at water level in humidifier = 7.5 cm water temperature in humidifier = 85°C, water temperature in dehumidifier = 10°C.

4. Conclusion

An experimental investigation is carried out to study the performance of water heated and air heated bubble column HDH system under different operating conditions. The water heated bubble column HDH system has higher productivity and GOR compared to the air heated system. Freshwater production and input heat increase with increasing airflow rate and water temperature in a humidifier. However, GOR is governed by the rate of increase of production vs. the rate of increase in input energy. A higher rate of production increases GOR as long as the heat input is controlled. Nevertheless, water temperature in the dehumidifier has an impact on the performance. The production decreases with increasing water temperature in the dehumidifier, due to the decrease in temperature difference between warm air and colder water in the dehumidifier. This leads to a decrease in the rate of vapor condensation. Nevertheless, GOR increases with increasing water temperature in the dehumidifier due to the decrease in input cooling energy that has more impact on GOR than decreasing the production in this case.

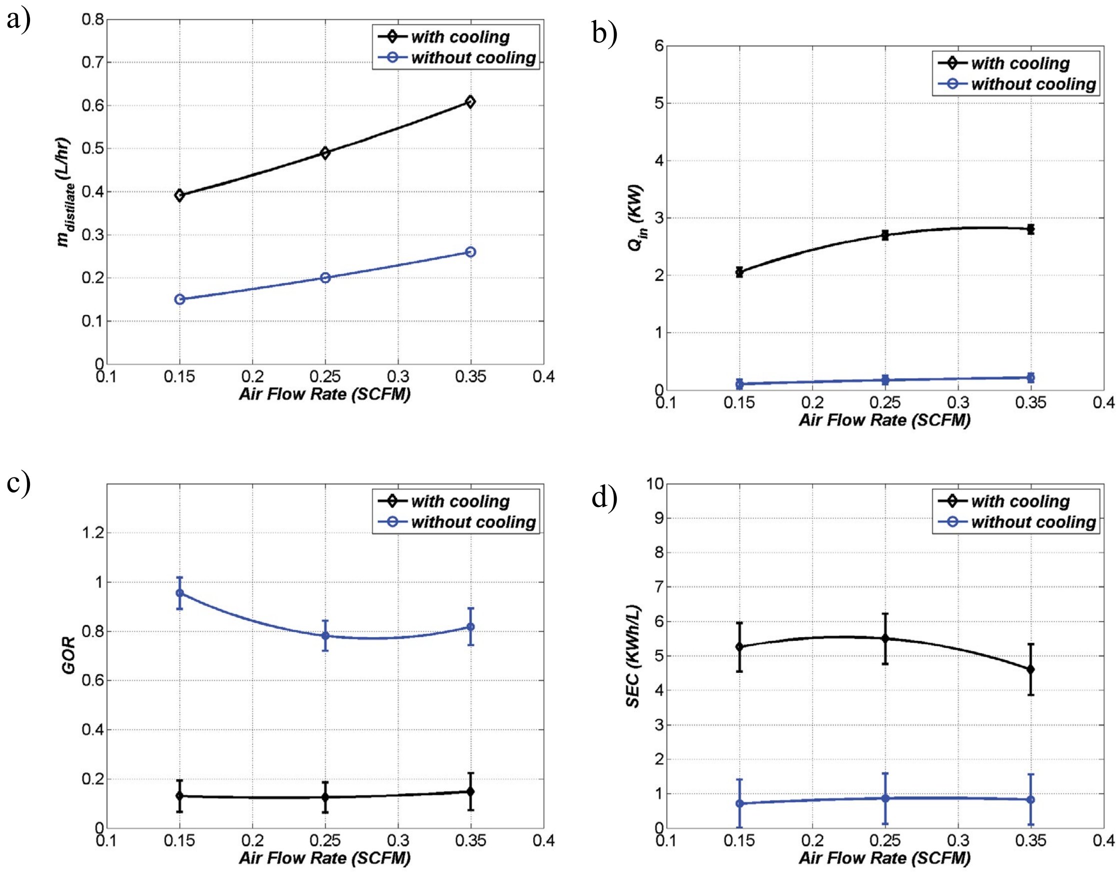

Fig. 11. Effect of airflow rate and water temperature in dehumidifier on (a) distillate, (b) Q_{in}, (c) GOR, and (d) SEC at a hot water temperature of 85°C, water level in a humidifier of 7.5 cm, and water level in dehumidifier = 8 cm.

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