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Performance evaluation of humidification-compression desalination

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ABSTRACT

The performance of humidification-dehumidification desalination, in which dehumidification is carried out by compression, was studied experimentally. A test rig was designed and assembled based on a new idea. In this system, the carrier gas is humidified through direct contact with hot water; and after humidification, the humid air is compressed by a compressor and cooled in a heat exchanger to recover the humidity as desalinated water. The effects of water-to-air ratio, water and air inlet temperatures, operating pressure, and condenser temperature on desalination performance were examined. It was found that the increase in temperature of the feed water and/or inlet air to the humidifier increased the water production rate and gain output ratio (GOR) of the system. The water-to-air ratio showed an increasing-decreasing trend in relation to the water production rate and GOR of the system; the best water-to-air ratio was found to be 2.

Keywords: Humidification-Compression; Parametric study; Desalination; Humidification-Dehumidification

1. Introduction

World population growth with the accompanying increase in industrial and agricultural activity has resulted in excessive exploitation of water resources and the pollution of fresh water resources. It has become necessary to use different methods to convert polluted water or saline water into potable water. One popular method to produce potable water is desalination, by which saline water is converted into potable water by the removal of the salt content. One of the most flexible thermal desalination methods in arrangement, operating conditions, and capacity is humidification of a carrier gas [1–4]. There are three main techniques for desalination by humidification of carrier gas: humidification-dehumidification (HDH) [5], humidification-compression (HC) [6] and dew-vaporation [7].

HDH is based on the fact that air can carry large quantities of water vapor. The ability to carry air increases as the temperature of the air increases: 1 kg of dry air can carry 0.5 kg of vapor when the air temperature increases from 30 to 80°C. When hot air is brought into contact with saline water, vapor is extracted by the air. Distilled water can be recovered by bringing humid air into contact with a cold surface, which causes condensation of the vapor and extraction from the humid air [8]. For desalinization, condensation generally occurs in an exchanger in which saline water is preheated by the latent heat of condensation.

HDH is especially suited for seawater or brackish water desalination in arid regions when the demand for water is decentralized [9]. Chang et al.

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experimentally investigated a multi-effect solar desalination based on HDH [10]. They used packed porous plastic balls and finned heat exchangers and measured the operating parameters of heating temperature, seawater flow rate, and air flow rate on system performance. The gain output ratio (GOR) and yield of the device were calculated from the temperature and flow rate under different operating conditions. The experimental results indicated that the yield of the system increased as the water flow rate and the air flow rate increased; the yield of the unit reached 6.3% and the GOR reached 2.1. Kang et al. developed a mathematical model for a dual-effect system based on HDH and reported 72.6 kg/h water production and 2.44 GOR [11]. GOR or performance ratio (PR) is an efficiency criterion and is defined as the ratio of the mass of water produced by a desalination process over a fixed quantity of energy consumed. In many practical cases, steam may not be the medium of heat transfer, so GOR is most commonly defined as the mass, in pounds, of water produced by desalination per 1,000 BTU of heat provided to the process. The SI equivalent of this formulation is the number of kg of water produced per 2,326 kJ of heat [12]. This parameter is shown as Eq. (1) in SI units system.

$$\mathrm{GOR} = \frac{\text{kg of produced water}}{\text{kJ of energy consumption}} \times 2326 \tag{1}$$

In Eq. (1), all sources of energy consumption, such as electrical, fuel, steam, and so on, should be considered into account.

Li et al. [13] designed and tested a solar air heater with evacuated tubes for the solar HDH. The test results showed that the cut length of efficiency was 0.47 and the overall heat loss coefficient was 1.60. The humidifier and dehumidifier were designed and optimized using mathematical methods, and a desalination pilot plant was designed and built. Test results on operating characteristics showed that the increase in inlet-sprayed water temperatures from 9 to 27°C in the pad humidifier effectively improved the relative humidity of the moist outlet air from 89 to 97% and increased the outlet air temperature from 35 to 42°C. Sometimes, the HDH systems are combined with other facilities such as air conditioning system. Nada et al. investigated the combined effect of HDH system with an air conditioning system. It was found that the fresh water production rate could be increased by increasing the air humidity and air flow rate [14].

Yildirim and Solmus [15] theoretically investigated the performance of a solar-powered HDH desalination system under different operating and design parameters for the climatological conditions of Anatolia, Turkey. The primary components of the system were a flat plate solar water heater, flat plate double pass solar air heater, humidifier, dehumidifier, and storage tank. The mathematical model of the system was developed and governing-conservation equations were numerically solved using the fourth-order Runge–Kutta method. Also it was found that the effect of water heating on water production rate is much higher than air heating.

Mohamed and El-Minshawy [16] studied the desalination of sea water using a HDH system supplied with water heated by geothermal energy. The effect of sea water-to-air mass flow ratio, difference in cooling water temperature across the condenser, geothermal source inlet temperatures to the heat exchanger, and the amount of distilled water produced was studied. Experimental and theoretical results were compared to validate the results and a good agreement was observed. The results showed that the optimum ratio of sea water mass flow to air mass flow was 1.5–2.5. Improvement in freshwater productivity at the optimum ratio of sea water mass flow to air flow was observed when the geothermal source inlet temperature and the cooling water temperature difference increased across the condenser. The thermal performance of a HDH system (closed-air and open-water arrangement) was evaluated by the GOR and the efficiency of the water solar collector in Zhani work [17]. The results illustrate that the collector efficiency is increased by the increase in water flow rate and the decrease in feed water temperature. Also the maximum GOR is gained in water to air mass flow ratio of 3.5.

Kabeel et al. [18] experimentally investigated a desalination system based on HDH. The influence of inlet water temperature and inlet water mass flow rate to the humidifier on the performance of the HDH unit was studied. The optimal ratio of cold water at the condenser inlet to hot water at the evaporator inlet (C/H) was found to be 2. Kabeel and El-Said [19] studied solar radiation, feed water mass flow rate, inlet cooling water temperature, mass flow rate of cooling water, and nanoparticle volume fraction for a solar HDH-SSF system. It was found that the PR of SSF (water-flashing evaporation) unit varied from 0.32 to 1.4 and the flashing ranged from 3 to 9°C. The maximum productivity of the system was 41.8 kg/d under experimental conditions. The solar water heater efficiency was affected by the nanoparticle volume fraction. Humidifier efficiency was more influenced by an increase in the water mass flow than by the increase in air mass flow and reached about 98%.

The present study investigated desalination performance of an efficient process, previously introduced as HC under different operating conditions. The details of this process have been presented in a previously published study [6]. Here, the effect of operating conditions and parameters on the performance of a HC desalination test rig was examined to determine the optimal operating conditions.

2. Materials and methods

2.1. Materials

Brackish water taken from a well (33°50′38′′N and 54°56′59′′E) in Khur, Iran was used as the feed for all experiments. Table 1 lists the characteristics of the brackish water.

2.2. Apparatus

The desalination apparatus was a HC test rig. In this apparatus, brackish water (feed water) enters the double-pipe heat exchanger (24 m in length and 1.58 m^2 in area) and is heated by hot air discharged from the compressor. After heating, the total quantity of feed water enters through the top of the humidifier (100 mm in diameter and 2,000 mm in length) and comes into contact with air flowing from the bottom to the top of the column. Table 2 lists the packing specifications of the vertically packed-column humidifier. Water vapor forms and the concentrated water (brine) is discharged from the bottom of the humidifier.

The humid air is discharged from top of the humidifier column and enters a polytropic compressor (twin-driven reciprocating type with eight-bar maximum pressure). The air temperature increases during compression. Heated air enters the double-pipe heat exchanger and is cooled (and partially condensed) by the brackish water. The humid air then enters the flash drum and the desalinated water is separated. After cooling of humid air in the condenser, the circulated air needs to be heated again. So the discharged air from the flash drum is returned to the humidifier after heating in the solar heater (1.5 m^2 in area) and decreasing its pressure. All temperatures and humidity are measured using a data transmitter made by “KIA Process Design Engineers, Iran” with ±0.5°C temperature and 1% relative humidity accuracy. Air and water flow rates are measured by two rotameters with 2% accuracy of upper limit (upper limit for air flow rate is 16 m^3/h and for water is 1,000 mL/min), which are made by “Scientific Devices Pvt. Ltd, India.” Also, pressure is measured by a pressure gage made by “C. B. Corporation, India” with ±3 kpa accuracy. Fig. 1 is a process flow diagram for the apparatus. Fig. 2 shows the desalination apparatus.

Table 1
Brackish water characteristics

Parameter	Value
Total dissolved solid (TDS)	8,030 mg/L
Electrical conductivity (EC)	11,900 μs
pH	8.0
CO_3^{2-}	0.0 meq/L
HCO_3^-	2.3 meq/L
Cl^-	100.0 meq/L
SO_4^{2-}	21.9 meq/L
Ca^{2+}	9.5 meq/L
Mg^{2+}	8.5 meq/L
Na^+	106.0 meq/L
K^+	0.2 meq/L

Table 2
Humidifier and packing specification

Parameter (unit)	Value
Type	Rasching ring (ceramic)
Packing size	½″ (1.5 × 1.5 × 2 mm)
Apparent weight (kg/m^3)	700
Apparent average number (N/m^3)	200,000
Apparent surface area (m^2/m^3)	310
Packing free volume	70%
Bed length	1,500 mm

2.3. Methods

Testing was carried out to show the effect of operating conditions on system performance at five levels as follows:

(1) Water and air temperature, system pressure, and air humidity were held constant and water-to-air flow ratio was tested at five levels.
(2) Water temperature, system pressure, air humidity, and water-to-air flow ratio were held constant and inlet air temperature into the humidifier was tested at five levels.
(3) Water and air temperature, system pressure, and water-to-air flow ratio were held constant and inlet air humidity into the humidifier was tested at three levels.
(4) Water and air temperature, air humidity, and water-to-air flow ratio were held constant and condenser pressure was tested at three levels.

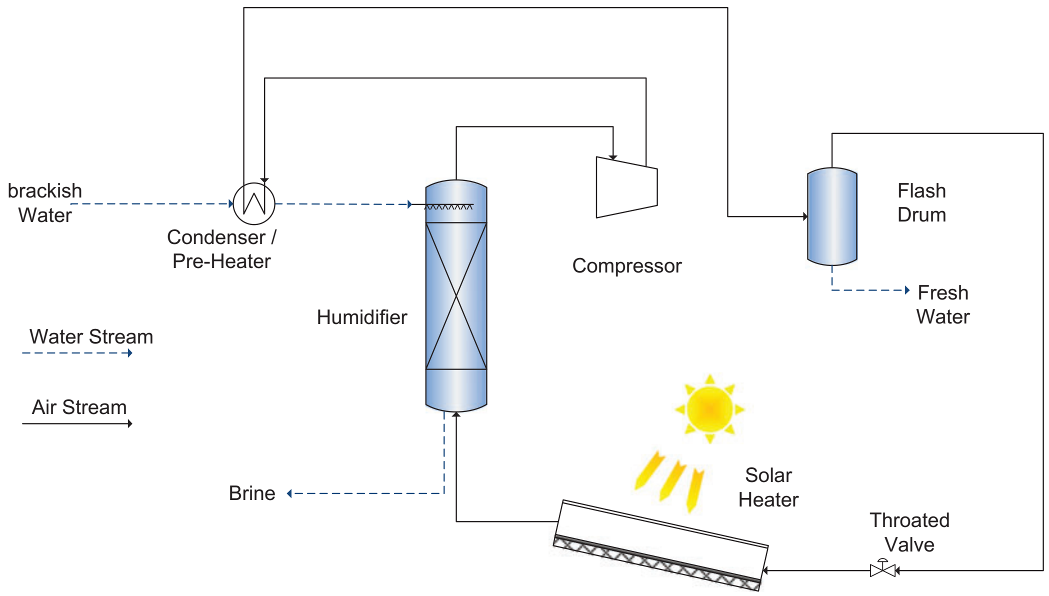

Fig. 1. Process flow diagram for the HC desalination apparatus.

Fig. 2. HC apparatus.

(5) Air temperature, system pressure, air humidity, and water-to-air flow ratio were held constant and water temperature was tested at three levels.

Some experiments were repeated two or three times randomly and the deviation between the experiments was below 3%.

3. Results and discussion

Five sets of experiments were carried out under Isfahan, Iran environmental conditions, while the system performance was monitored. All operating conditions were held constant and the parameter under study was varied. Table 3 lists the ranges of operating conditions studied.

Some parameters or operating conditions are dependent. The independent parameters were air and water flow rates, condenser pressure, feed water temperature, and solar collector area; the others were regulated by the independent parameters.

3.1. *Effect of water-to-air flow ratio*

The effect of five levels of water-to-air flow ratio on the system performance was studied at a constant air flow rate. Fig. 3 shows that the water production rate and GOR increased initially as the water-to-air flow ratio increased and then decreased. Increasing the water flow rate decreased the condenser temperature and increased water recovery from the air. Increasing the water flow rate decreased the inlet water temperature to the humidifier, which decreased the efficiency of the air humidification process. So, GOR and water production rate have increasing trends before reaching to the optimum value of water-to-air ratio and after that point increasing the water-to-air ratio inverses the trends.

Fig. 4 shows the effect of water-to-air ratio on outlet air temperature from the condenser and outlet air

Table 3
Operating conditions' domain

Operating condition	Value (unit)	Base of experiment
Air flow rate	10 (kg/h)	10 (kg/h)
Water flow rate	12–36 (kg/h)	24 (kg/h)
Water/Air flow ratio	1.2–3.6	2.4
Condenser pressure	2.0–3.0 (bara)	2.5 (bara)
Feed water temperature	4–26 (°C)	26 (°C)
Inlet air temperature to heater	20–52 (°C)	38 (°C)
Inlet air temperature to humidifier	46–77 (°C)	74 (°C)
Inlet air humidity to humidifier	0.006–0.035 (kg/kg air)	0.0174 (kg/kg air)
Outlet air temperature from humidifier	51–74 (°C)	71 (°C)
Outlet air humidity from humidifier	0.054–0.156 (kg/kg air)	0.135 (kg/kg air)
Inlet water temperature to humidifier	52–98 (°C)	77 (°C)
Outlet water temperature from humidifier	42–54 (°C)	50 (°C)

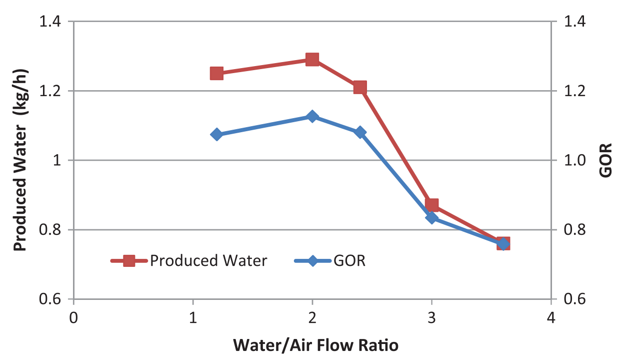

Fig. 3. Effect of water-to air flow ratio on water production rate and GOR at 10 m^3/h air flow, 1,000 W/m^2 solar rate, and feed water temperature of 26°C and 2.5 bar condenser pressure.

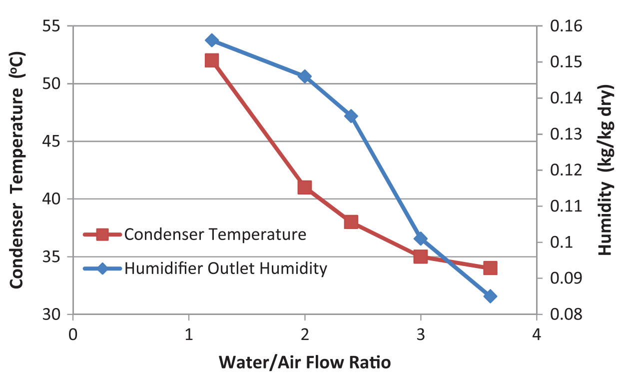

Fig. 4. Effect of water-to-air flow ratio on condenser outlet temperature and humidifier outlet humidity at 10 m^3/h air flow, 1,000 W/m^2 solar rate, and feed water temperature of 26°C and 2.5 bar condenser pressure.

humidity from the humidifier. As shown, increase in the water flow rate increased the condenser heat duty and decreased the condenser temperature, which means that the humidity recovered from the air increased as the amount of water fed into the condenser water increased. An undesirable effect of increased water flow is decreased humidification efficiency in the humidifier. When the water flow rate increased, inlet water temperature to the humidifier decreased; this decreased the water vapor pressure in the humidifier and decreased humidification. So, an optimum water-to-air ratio exists to maximize GOR. For this system, the optimum value obtained from the experimental investigation was about 2, which conforms with the results of previous studies [16,18].

3.2. Effect of inlet air temperature

To test the effect of inlet air temperature on system performance, the outlet air temperature from the solar heater was varied by changing the effective area of the solar collector. Fig. 5 shows the effect of inlet air temperature to the humidifier on the water production rate and GOR. As shown, GOR and water production rate slightly increased linearly as the inlet air temperature increased. Increase in the inlet air temperature into the humidifier increased the water film temperature (surface between the air and water along the humidifier) and water vapor pressure. This increased the humidification rate by increasing the air temperature. Because of lower air stream enthalpy (against water stream), inlet air temperature variation could not significantly affect the air humidity and water temperature profile through the humidifier. In fact, the most important term in water energy equation is enthalpy change due to evaporation process; thus, the variation of inlet air temperature has no significant

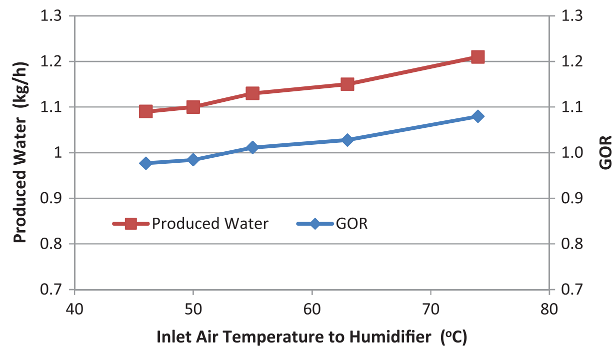

Fig. 5. Effect of inlet air temperature to humidifier on water production rate and GOR at 10 m^3/h air flow, 1,000 W/m^2 solar rate, 2.4 water-to-air flow ratio, and feed water temperature of 26°C and 2.5 bar condenser pressure.

effect on water temperature profile and consequently on GOR or water production rate as reported by Yildirim and Solmus [15].

In this system, the compressor plays the main role; and according to the results that are obtained in Fig. 5, environmental conditions (ambient temperature, solar radiation rate, and so on) are of secondary importance on the system performance. So, the system has a good performance during the day.

3.3. Effect of inlet air humidity

Fig. 6 shows that an increase in inlet air humidity to the humidifier slightly increased the water production rate and GOR. Since the difference between the saturation humidity near the water surface through the humidifier and air humidity is very high and because no changes occur in humidifier mass transfer coefficient by changing the inlet air humidity, it is better to enter the air into the humidifier under saturated condition. Under constant conditions, higher inlet humidity in the humidifier results in higher water production in the flash drum; but due to dependency of air humidity to condenser temperature, there is a limited range for changing the air humidity.

3.4. Effect of condenser pressure

Condenser pressure is one of the most important parameters in the proposed system and affects the other parameters. Fig. 7 illustrates the effect of condenser pressure on water production rate and GOR. Increase in the condenser pressure (increasing compressor outlet pressure) increases the outlet air temperature from the compressor and the inlet water temperature into the humidifier. Heat recovery and vapor recovery also increased, which increased the water production rate. Increase in the condenser pressure increased the power consumption by the compressor; both energy consumption and water production are increased; so, no change was observed in the GOR (because the numerator and denominator of GOR equation are increased at the same time) under chosen operating conditions. Pressures higher than 3 bar can greatly increase air temperature; thus, the experiments were carried out below 3 bar. High temperature significantly increases the cost of the equipment and decreases the economy of the process.

3.5. Effect of feed water temperature

Fig. 8 shows the effect of feed water temperature on the water production rate and GOR. Increase in the feed water temperature increased the inlet water temperature into the humidifier and can increase the humidification performance. At feed water temperatures of 4, 16, and 26°C, inlet water temperatures into

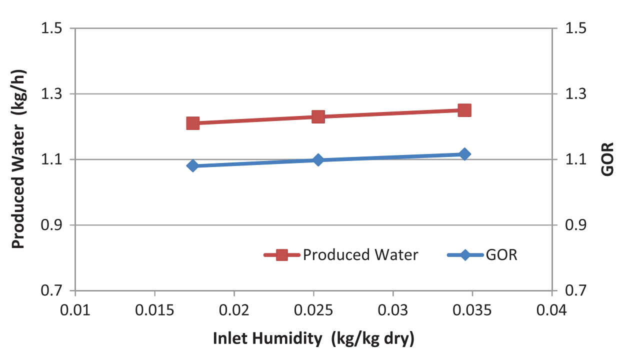

Fig. 6. Effect of inlet air humidity to humidifier on water production and GOR for 10 m^3/h air flow, 1,000 W/m^2 solar rate, 2.4 water-to-air flow ratio, and feed water temperature of 26°C and 2.5 bar condenser pressure.

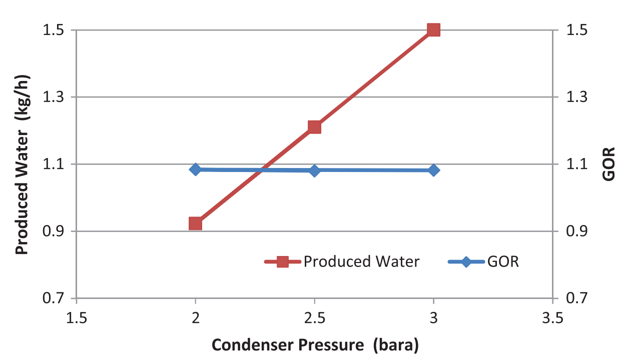

Fig. 7. Effect of condenser pressure on water production rate and GOR for 10 m^3/h air flow, 1,000 W/m^2 solar rate, 2.4 water-to-air flow, and feed water temperature of 26°C.

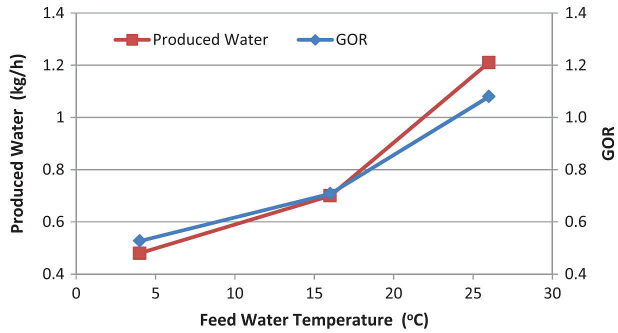

Fig. 8. Effect of feed water temperature on water production rate and GOR for 10 m^3/h air flow, 1,000 W/m^2 solar rate, 2.4 water-to-air flow ratio, and 2.5 bar condenser pressure.

the humidifier were 52, 61, and 77˚C, respectively. At lower feed water temperatures, vapor recovery in the condenser was better, but the effect of feed water temperature on humidification was higher than for vapor recovery. Generally, increase in the feed water temperature increased the water production rate and GOR. It is predicted that in feed water temperatures higher than 26˚C, the water production rate and GOR are increased intensively; but the feed water temperature in summer cannot exceed 26˚C under Isfahan environmental conditions; so, higher feed water temperatures were not examined in this investigation. Also for simulation of winter season, chilled feed water (with 4˚C) is used in the experiments.

4. Conclusion

The performance of a new type of carrier gas humidification process that was introduced as "Humidification-Compression" system was investigated. It was found that the most important parameters affecting GOR are water-to-air flow ratio and feed water temperature. The other parameters studied had no significant effect on GOR under the chosen operating conditions. Increase in the inlet water temperature and inlet air temperature to the humidifier increased the water production rate, but the effect of increased water temperature was more significant. Increase in the condenser pressure increased water production rate, but it had no significant effect on GOR. The best water-to-air flow rate for the proposed system that maximized GOR was about 2. The main operating parameter for process optimization is the feed water flow rate (or water-to-air ratio) over operating constraints such as condenser pressure, solar heater temperature, and feed water temperature.

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