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Performance assessment of a cross-flow packed-bed humidification–dehumidification (HDH) desalination system – the effect of mass extraction

Dahiru U. Lawal[a], Mohamed A. Antar[a,b,*], Abdelrahman Aburub[a], Mansur Aliyu[a]

[a]*Mechanical Engineering Department, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia, emails: antar@kfupm.edu.sa (M.A. Antar), dahiru@kfupm.edu.sa (D.U. Lawal), s201264380@kfupm.edu.sa (A. Aburub), mnsraliyu@kfupm.edu.sa (M. Aliyu)*
[b]*Center of Research Excellence in Water Desalination, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia*

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ABSTRACT

This paper presents an experimental investigation of a cross-flow packed-bed humidification–dehumidification (HDH) desalination system. The influence of mass flow ratio (MR), feed temperature, and cold water flow rate on the system performance indicators such as system productivity, gain output ratio (GOR), recovery ratio (RR), and components (humidifier and dehumidifier) effectiveness values is investigated and discussed. The study equally examines the impact of stream extractions and injections on the performance of HDH system through mass balancing, which minimizes the entropy generation in the system. The results show that the system is capable of producing distillate water of about 144 L/d and can reach a GOR of 2.7, and RR of 1.33%. Furthermore, the obtained results suggest that it is possible to improve the cycle performance through mass balancing, as we recorded an improvement of about 68%, 4%, 17%, 12%, and 2% for GOR, productivity, RR, humidifier effectiveness and dehumidifier effectiveness, respectively, over the baseline case (without mass balancing).

Keywords: Desalination; Experiments; humidification–dehumidification; Mass balancing; Cross-flow; Extraction; Injection

1. Introduction

The gap between the demand and supply of freshwater resources is ever increasing due to rapid population growth, urbanization, and climate change [1,2]. The quest for better fresh water production has consistently put researchers in search for superior and most efficient potable water production technology [3]. Desalination of sea and brackish waters has become a necessity in many countries of the world, especially those in arid and semiarid regions [4,5]. Desalination of saline waters required an increasingly important and widespread technologies to alleviate the global problem of potable water scarcity. Many desalination technologies including humidification–dehumidification (HDH) [6–9], membrane distillation [10], and other conventional desalination techniques have been investigated and proved to be suitable solutions to freshwater crisis all over the world. HDH is one of the promising thermal desalination methods that uses air as a carrier gas to distill pure water. Some of the features of HDH technique include accommodation for low-grade energy, simple in design, and easy to manufacture. HDH system is especially suitable for decentralized and small-scale desalination demand [11,12]. The main component of HDH cycle includes a humidifier, a dehumidifier, and a medium (water or air) heater. There are several design configurations formed with different components and cycles that have been proposed and analyzed by researchers. HDH cycles may be classified according to whether air or water is heated and according to whether the air or water circuit is open or closed

* Corresponding author.

loop. This classification includes either water-heated or air-heated for; closed-water open-air cycle, open-water open-air cycle, and open-water closed-air cycle [13].

To achieve the best design concepts of HDH systems such as reduced energy consumption and improved freshwater production, sizeable amount of research work has been carried out [14]. Sharqawy et al. [15] investigated numerically the design, performance, and optimization of two HDH cycles; a water-heated cycle and modified air-heated cycle. They presented first-law based thermal analysis model, as well as performance charts, which can be used to determine the sizes of HDH system under different design conditions. In another study, Saeed et al. [16] numerically investigated the performance of a simple HDH cycle taking place in a rectangular enclosure (cavity) of different aspect ratios. A computational model is developed for predicting the velocity, temperature, concentration fields, as well as the rate of water evaporation within the cavity. Their results showed that an aspect ratio of 1.5 yields the highest heat and mass transfers. Zubair et al. [17] numerically optimized an HDH desalination system integrated with solar evacuated tube collectors. The optimized system was examined for the operation in different geographical locations. Their finding indicated that Sharurah and Dhahran provide the maximum and minimum productivity of freshwater, respectively. The cost of freshwater production was also investigated and was found to vary from \$0.032 to \$0.038/L.

In another development, Sharqawy et al. [18] conducted an experimental study to examine the performance of a cross-flow packed-bed humidifier. The influence of mass flow ratio (MR) on the humidification capacity, saturation efficiency, and specific energy consumption by the system was assessed. They also adopted an effectiveness model developed for cross-flow packed-bed cooling tower to estimate the effectiveness of the humidifier. The model was found to be in a good agreement with the experimental data with about 6% deviation from the experimental measurements at high capacity ratio. Aburub et al. [19,20] experimentally assessed the performance of a packed-bed cross-flow HDH desalination system. They designed, constructed, and investigated the performance of the system with a closed water (brine recirculation), open-air configurations. Their results showed that the built system is capable of producing distillate water of 92 L/d and can reach a maximum GOR of about 1.3. Yamali and Solmus [21] under the climatological conditions of Ankara experimentally assessed the performance of a solar-driven cross-flow HDH desalination process. Their results showed that the system productivity decreases by 15% if double-pass solar air heater is not used. Increasing the feed water mass flow rate and quantity of water inside the storage tank was reported to have increased the productivity of the system. Al-Sulaiman et al. [22] examined experimentally the performance of a novel bubble column humidifier operated by solar thermal energy. The system performance was examined with and without Fresnel lens. Their results show about 12.3% increment in average daily absolute humidity of the air at the exit of the humidifier.

It has been reported that the performance of HDH system can be improved by balancing the humidifier or the dehumidifier thermodynamically [23]. Balancing the system is reported to reduce the entropy generation of the system. The system balancing is done by extracting fluid from either water or air stream in one component and then injecting it into the other component [23]. Mistry et al. [24] applied irreversibility analysis to characterize HDH desalination cycles and identified ways to improve cycles and components. They show that minimizing the specific entropy generation of the cycle maximizes the gained output ratio of the system. They also illustrate how irreversibility analysis can help a designer to optimize HDH cycles. Thiel et al. [25] investigated the effects of mass extraction/injection on cycle performance by developing models describing fixed-size humidifiers and dehumidifiers for use in HDH systems. The gain output ratio (GOR) was found to increase by about 10% through a single extraction from the dehumidifier to the humidifier on a thermodynamically optimized HDH system. Narayan et al. [26] experimentally investigated the performance of a pilot-scale HDH unit which has a peak production capacity of 700 L/d. Their experimental data were used to validate previously developed theories behind the design of HDH systems with or without mass extraction and injection. Furthermore, they showed that mass extractions from the humidifier to the dehumidifier increased the GOR of the water heated OWCA HDH system by up to 55%.

From the foregoing discussion, it has been noticed that mass extractions and injections improve the performances of HDH system considerably. However, most of the reported work in relation to mass balancing were purely thermodynamic and numerical in nature. Furthermore, the available investigations were conducted on counter-flow HDH arrangement, other than cross-flow packed-bed HDH configuration. It has also been observed that cross-flow packed-bed HDH arrangement has not received its due attention, and its performance has not been properly understood. Moreover, compared with counter flow humidifier arrangement, cross-flow humidifier arrangement offers several benefits including higher effectiveness, lower pressure drop, smaller footprint, and easier balanced operation. Thus, more investigations are required to analyze and provide better understanding on the performance of cross-flow packed-bed HDH system configuration. Hence, the objective of the current work is to assess the performance of a cross-flow packed-bed HDH desalination system experimentally, and to further enhance its performance through mass extractions and injections, which reduces the system irreversibilities (reduced entropy generation in the system).

2. Description of working principle and experimental setup

2.1. Process description

The schematic line diagram of the cross-flow water-heated HDH system is shown in Fig. 1. Hot water from the hot-water tank is sprayed in the humidifier over a structured type packing material to increase the surface area for effective heat and mass transfer. A portion of water evaporates in the air stream, while the rest is rejected through the bottom of the humidifier. The rejected hot water flows downward and returns to the hot-water tank (brine recirculation designed). Air flows through the packing material situated in the humidifier in a cross-flow direction. It is then heated

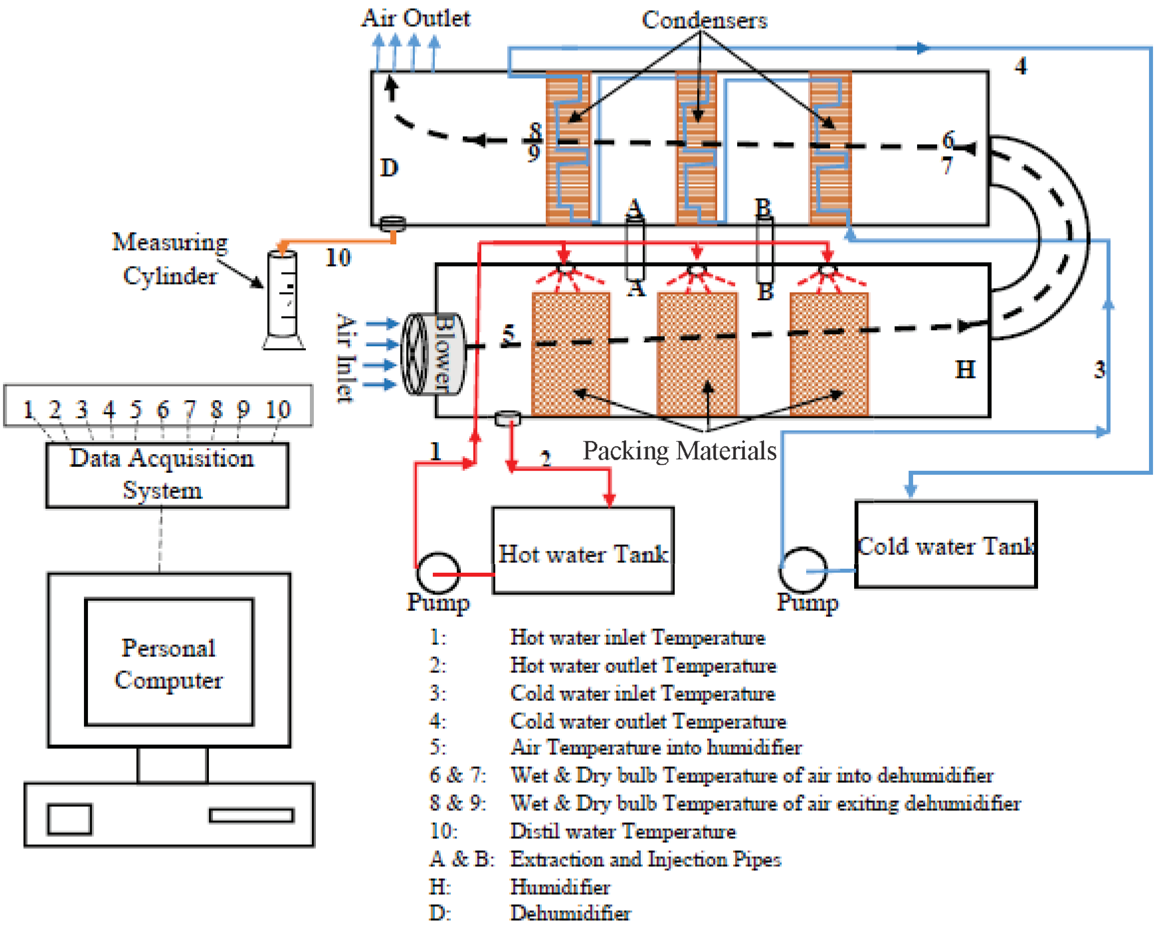

Fig. 1. Schematic line diagram of the setup.

and humidified through direct contact with the sprayed hot water. The hot-humid air then flows to the dehumidifier where water vapor present in the humidified air condenses to produce fresh water, and the cold air is ducted out of the dehumidifier. Cold water from the tap flows through the condensers located in the dehumidifier, and condenses the water vapor present in the humidified air. The cold water is discharged from the dehumidifier to water basin at a relatively higher temperature. It is worth noting that both air and cold water flows in an open loop while the hot water flows through a closed loop (brine recirculation).

The description of the system as presented in Fig. 1 is as follows: hot water leaves the tank at state (1). Then, it is pumped into sprayers placed above the packing material. Water is then collected at the bottom of the humidifier and drawn back to the tank (2) to be circulated. Air is blown into the humidifier (5) where it is heated and humidified, and then blown into the dehumidifier (6 and 7). The humidified air condenses and exits from the dehumidifier at points (8 and 9) after passing through the condensers in which cold water flows. Cold water enters the dehumidifier (3) and exits to the sink (4). Desalinated water is collected at the bottom of the dehumidifier (10) as a product of the system. The system is operated at atmospheric pressure, which is assumed to be 101.325 kPa. Hot water temperature and flow rate are varied at 55°C, 65°C, and 75°C and 6, 10, 14, and 18 L/min, respectively. While the cold water temperature was kept constant at 30°C ± 2°C, flow rates were changed at 4, 8, and 12 L/min. The system shown in Fig. 1 can be operated with/without mass extractions and injections through the control valves (A and B).

2.2. Experimental setup

A photograph of the designed, constructed, and tested experimental lab-scale setup is depicted in Fig. 2. The humidifier and dehumidifier units are made of Plexiglass material, and in the form of horizontal rectangular ducts connected by U-pipe (6″ PVC I) at one end. The humidifier has cross sectional dimensions of 30 cm × 30 cm and a length of 90 cm. Three structured-type packing material of 15 cm thickness, separated by a distance of 10 cm are installed inside the humidifier. Mist eliminators are installed at the downstream of the humidifier to strip the water droplets that are carried by the humidified air. The dehumidifier has a height of 25 cm, width of 30 cm and a length of 110 cm. Three condensers made from copper tubes and aluminum fins are installed inside the dehumidifier for effective condensation of water vapor. Each of the three condensers has a thickness of 5 cm, separated by a distance of 30 cm. Air at room temperature is blown through the humidifier and passes through the packing material by an axial flow air blower installed

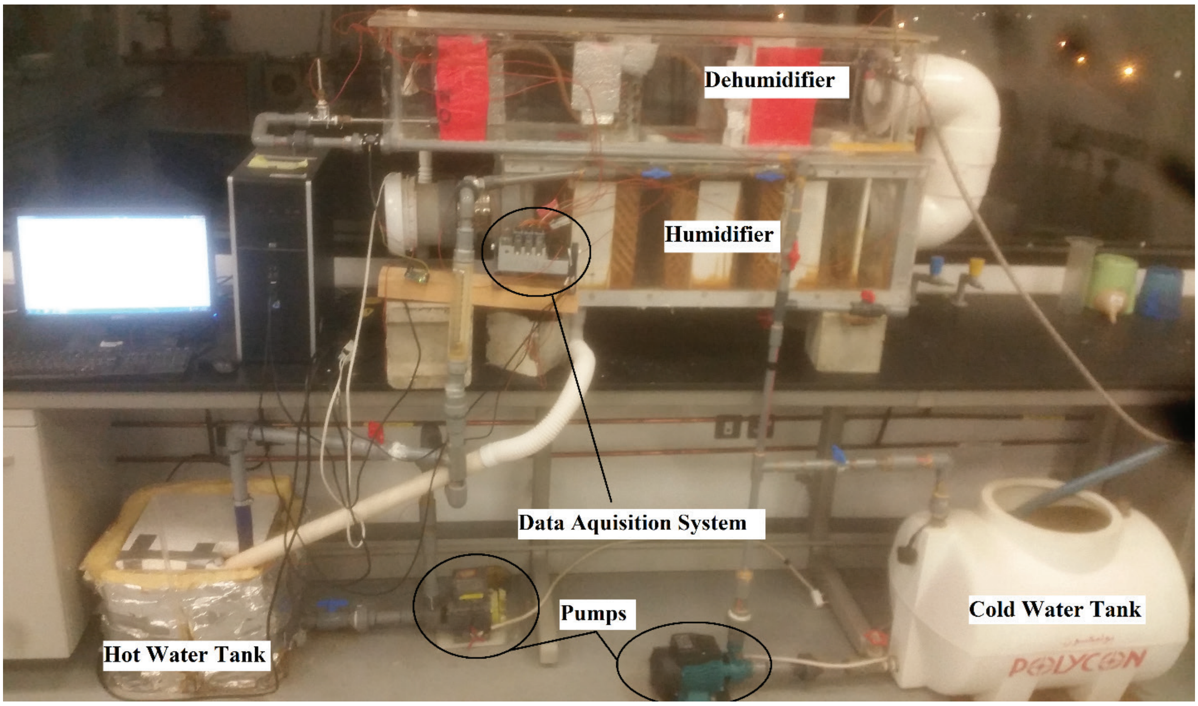

Fig. 2. A photograph of the actual laboratory setup and its components.

at the humidifier entrance. The hot brackish water tank is fitted with two electric heaters with each having a heating capacity of 2 kW.

The hot water tank is insulated to reduce heat loss and ensure steady and constant water temperature. Both hot and cold water were pumped through the humidifier and dehumidifier, respectively, using small centrifugal pumps, and ball valves are used to regulate the water flow rate. K-type thermocouples are installed at the inlet and outlet of the air and water streams to measure the dry bulb, wet bulb, and water temperatures. The thermocouple junction for the wet-bulb temperature measurement is wrapped with a wet wick supplied by water from gravity feeding syringes. All the measuring sensors are connected to the National Instrument (NI) data acquisition system (NI cDAQ-9174 module) and all measured values are monitored and stored on a computer using a LabVIEW code. Water flow rates are measured using in-line flow meters glass tube rotameter (Omega FL46300) of ±5% accuracy and a range of 4–36 LPM. The air velocity is measured at the dehumidifier exit using a digital anemometer (Smart Sensor AR 836) of ±3% accuracy. Pipes of 4 cm internal diameter located in-between the packing materials and condensers are used for the mass extractions and injections from the humidifier to dehumidifier, respectively.

3. Results and discussion

In this section, the impact of the HDH system operating parameters on the system performance is presented. The influence of feed water temperature, cold water flow rate and mass flow rate ratio on the system productivity, GOR, recovery ratio (RR), humidifier, and dehumidifier effectiveness is presented and discussed. Mass flow rate ratio (MR) is defined as ratio of the feed water flow rate to air mass flow rate. MR is calculated by varying the hot water flow rate while keeping the air flow rate constant from the fan. The mass flow rate ratio is varied from 0.6 to 1.7. It is worth noting that the water flow rate was adjusted such that MR is limited to 1.7 to avoid water flooding in the humidifier.

3.1. Effect of operating parameters on system productivity

Fig. 3 shows the system productivity in L/h as it changes with the mass flow rate ratio at different cold water flow rates, feed water temperatures, with and without mass balancing. As shown in the figure, the system productivity increases with mass flow rate ratio. Increasing MR means increasing feed water flow rate, which promotes flow turbulence level in the packing materials, leading to increased heat transfer coefficient and water vapor generation, hence fresh water production increases. The quantity of distillate collected is also noticed to increase with increasing top brine temperature (TBT), due to the greater water evaporation rate at higher temperatures. However, no significant changes were observed in the system performances for the variation in cold water flow rates 4–12 L/min as illustrated in Figs. 3–7. The effect of coolant flow rate on the system performance in all cases (Figs. 3–7) is observed to be marginal as long as the minimum flow rate needed for effective vapor condensation is maintained. Depicted in Fig. 3 is the influence of mass extractions and injections on the system productivity. The cases involving mass balancing provide higher condensate compared with that with no mass extractions and injections. The improved fresh water production is due to more uniform distribution of driving forces across the system, which further reduces irreversibility. The system could reach highest productivity of 5.7 L/h without extractions and injections. This value was further raised by about 4% to 6.02 L/h for the cases

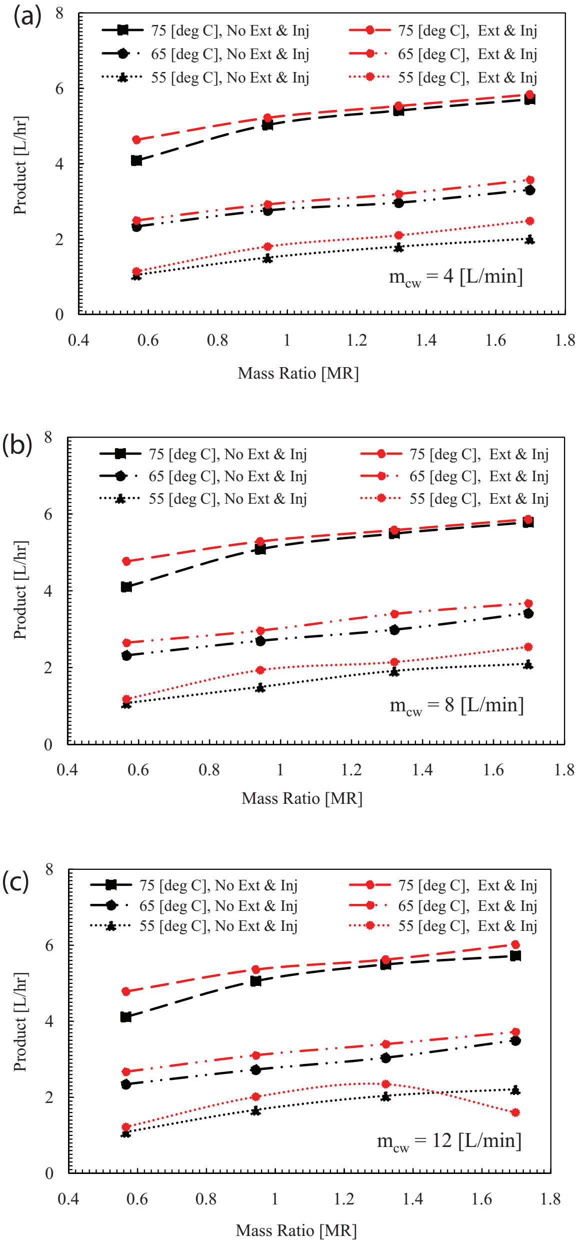

Fig. 3. Effect of mass ratio on system productivity at different hot water temperature with and without mass extractions and injections. (a) m_{cw} = 4 L/min, (b) m_{cw} = 8 L/min, and (c) m_{cw} = 12 L/min.

involving streams extractions and injections. For the lowest productivity, the system with mass extractions and injections recorded about 16% increment over the baseline case (without stream extractions and injections). The recorded average percentage rise in system productivity for the case with mass balancing over the baseline case is about 10%.

A performance ratio called the gained-output ratio (GOR) is the most important performance indicator for HDH system. It defines the energy performance for HDH and other thermal desalination systems. GOR is simply the ratio of latent heat of evaporation of the distillate produced to the total energy input into the system. This parameter is essentially, the effectiveness of water production and an index of the amount of the heat recovery in the system.

The GOR of the system is calculated using the following expression [15,27]:

$$\text{GOR} = \frac{\dot{m}_{\text{fw}} \times h_{\text{fg}}}{\dot{Q}_{\text{in}}} \tag{1}$$

where $\dot{m}_{fw}$ is the mass flow rate of the condensate, h_{fg} is the latent heat of vaporization (kJ/kg) and $\dot{Q}_{in}$ is the heat input to the system. It is important to mention that previous studies [25] reported that mass extraction of humid air (from the humidifier) and injecting it to the dehumidifier reduces flow imbalances that reduces irreversibilities and brings the modified heat capacity ratio closer to its optimum value of unity.

Since the system performance is measured in terms of GOR, higher values of GOR are always desirable. This can be achieved either by increasing the fresh water production rate for the same energy used, or obtaining the same fresh water flow rate with less input energy. As noticed in Fig. 4, the system GOR increases with the increase in mass flow rate ratio and decreases with increasing top brine temperature (TBT). Increasing MR increases the system productivity, which is directly proportional to the GOR of the system. This is because higher MR means higher flow rate of water. This provides an ample opportunity for air to carry more water vapor and its humidity increases accordingly. It is obvious from the figures that high TBT leads to lower system GOR, because of the increase in the net increment in required heat input (inversely proportional to GOR) to raise the water temperature. As reported by Thiel et al. [25], stream extractions and injections can minimize entropy generation by reducing flow imbalances, or remnant irreversibilities. These imbalances, which are equivalent to departures from a uniform distribution of driving temperature or concentration difference increase entropy generation. Hence, streams extractions and injections can result in smaller driving forces, less irreversibility, and thus a lower heat requirement and higher GOR. In Fig. 4, we observe that without mass balancing, the GOR of the system is relatively low due to the entropy production caused by non-ideal humidifier and dehumidifier temperature and concentration profiles [28]. The highest GOR that could be reached by the system without stream extractions and injections was 1.67 at MR of 1.7, and this value was raised by about 68% to 2.68 at MR of 1.7 through stream extractions and injections that leads to less imbalanced system.

Another important measure of performance of HDH system is the recovery ratio (RR) and the parameter is sometime referred to as the extraction efficiency (EE) [11,29]. RR is the ratio of the rate of pure water production to the rate of feed water entering the system. RR has a direct relationship with the rate of fresh water production. The expression for the RR is given as [15,20]:

$$\text{RR}(\%) = \frac{\dot{m}_{\text{fw}}}{\dot{m}_f} \times 100 \tag{2}$$

where $\dot{m}_f$ is the feed water flow rate.

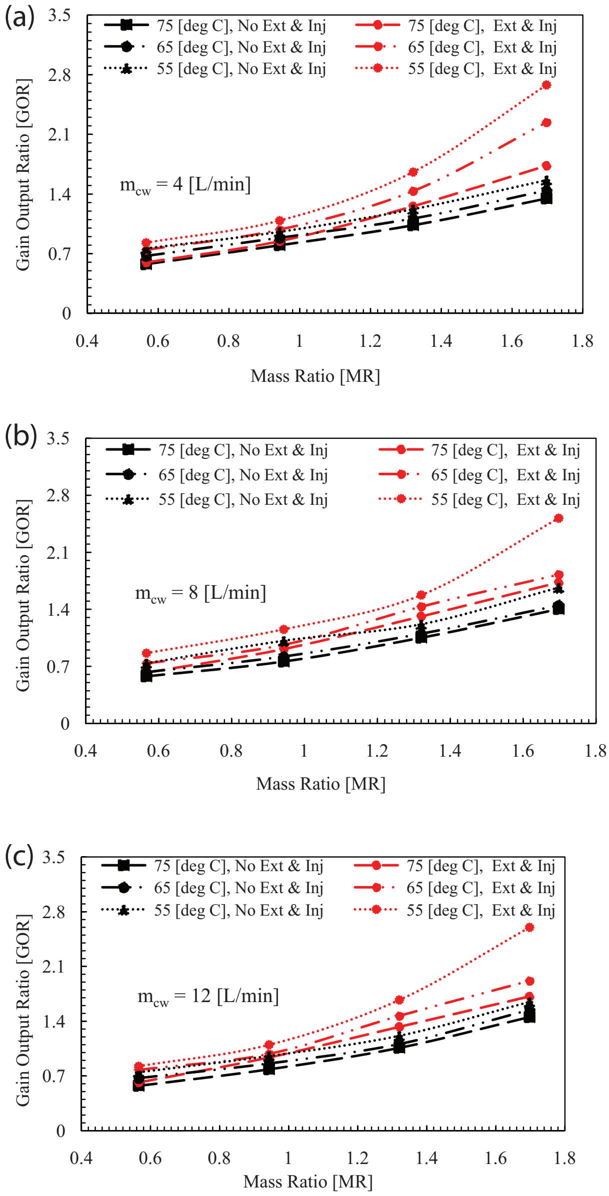

Fig. 4. Impact of mass ratio on gain output ratio at different hot water temperature with and without mass extractions and injections. (a) m_{cw} = 4 L/min, (b) m_{cw} = 8 L/min, and (c) m_{cw} = 12 L/min.

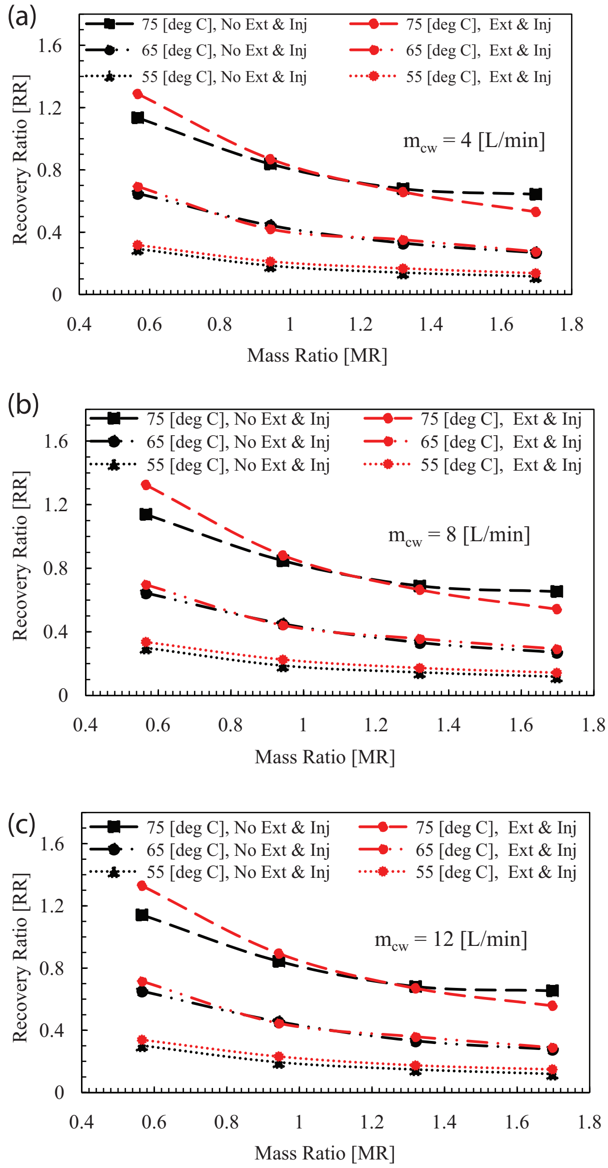

Fig. 5. Influence of mass ratio on recovery ratio at different hot water temperature with and without mass extractions and injections. (a) m_{cw} = 4 L/min, (b) m_{cw} = 8 L/min, and (c) m_{cw} = 12 L/min.

Presented in Figs. 5(a)–(c) is the impact of TBTs cold water flow rate and mass ratio (MR) on the RR. The RR is observed to decrease with increase in MR, and increase with increase in TBT. The reduction in RR is an indication that less amount of fresh water is produced per feed water. The RR decreases because the mass flow of feed per unit mass of air decreases at a faster rate than the mass flow of product water per unit mass of air. It is important to state, however, that as the humidity of the air increases, its ability to absorb more moisture decreases gradually due to the decrease in the concentration difference that is considered as the driving force for the mass transfer process. It can also be noticed that high TBT yields high RR. This is because at higher temperatures, in both the humidifier and dehumidifier, the interfacial humidity changes more rapidly; the significance of changing the effective capacity rate is thus more pronounced at those higher temperatures, and the rate of distillate production increases, leading to high EE. In other words, higher TBT causes more evaporation, leading to higher production rate, hence higher RR.

Figs. 5(a)–(c) also show the impact of stream extractions and injections on the system RR. Extractions and injections reduce the concentration differences that drive mass transfer along the humidifier and the dehumidifier. The highest RR that could be reached by the system size without stream extractions/injections was 1.14%, and this value was further increased by about 17% to 1.33% through mass extractions and injections, that resulted in more balanced and less irreversible operation of the system.

Most of the available work on HDH system in an open literature have been conducted based on fixed component (humidifier and dehumidifier) effectiveness. However, by varying the operation (boundary conditions) of an HDH system, the component effectiveness will change (increase or decrease with changes in boundary conditions), and only the physical sizes of the components will remain constant. The setback of a fixed component effectiveness analysis is that they cannot be used to compare different operating conditions for a given system because effectiveness is a strong function of the flow rates of the streams in the system [30]. Furthermore, it is difficult to translate the results of fixed effectiveness into practical recommendations, since the sizes of the exchangers used are not specified [30]. The humidifier effectiveness is calculated using the following expression [30]:

$$\varepsilon_H = \frac{\Delta \dot{H}}{\Delta \dot{H} + \dot{m}_{da} \Psi_{hum}} \tag{3}$$

where $\Delta\dot{H}$ is the change in the enthalpy rate of each stream, $\dot{m}_{da}$ is the mass flow rate of dry air (kg/s), and Ψ_{hym} is the enthalpy pinch in the humidifier (kJ/kg dry air).

Depicted in Figs. 6(a)–(c) and 7(a)–(c) is the variation of mass flow rate ratio and TBT on the humidifier and dehumidifier effectiveness values, respectively. The effectiveness of the humidifier and dehumidifier is defined as the ratio of actual enthalpy change ($\Delta\dot{H}$) of either air/water stream to maximum possible enthalpy change ($\Delta \dot{H}_{max}$) [27]. The maximum of either, water-side effectiveness or the air-side effectiveness is used as the component effectiveness. The effectiveness of both components is noticed to increase with increasing MR, and approach unity at higher MR, noting that increasing MR is an indication of more vapor generation and condensation. The increase of mass flow rate ratio also results in higher water heating capacity, which ensure keeping the water temperature high thereby heating and humidifying the air. The effectiveness of both humidifier and dehumidifier is also noticed to be influenced by variation in TBT. The humidifier effectiveness is observed to decrease with increase in TBT, while that of dehumidifier increases with TBT. The temperature difference between the rejected stream and the feed inlet stream to the humidifier decreases with increasing TBT, causing the humidifier effectiveness to be lower at high TBT. High effectiveness corresponds to smaller terminal temperature differences as well as a smaller stream-to-stream temperature variation along the length of the components. At small terminal temperature differences, the temperature profiles of the two streams get considerably closer to one another. In addition, the effectiveness of the humidifier is shown to be better at lower TBT since the maximum value is harder to reach at high TBT. The dehumidifier effectiveness on the other hand is found to be better at higher TBT, because of larger temperature difference between the incoming stream and outgoing stream from the dehumidifier. When TBT is high, vapor leaves humidifier to dehumidifier at high temperature. The fact that cooling water temperature remains constant irrespective of the value of TBT creates wider terminal temperature difference between the inlet and outlet of the flowing stream, thus leading to higher dehumidifier effectiveness. The dehumidifier effectiveness also increases with the water

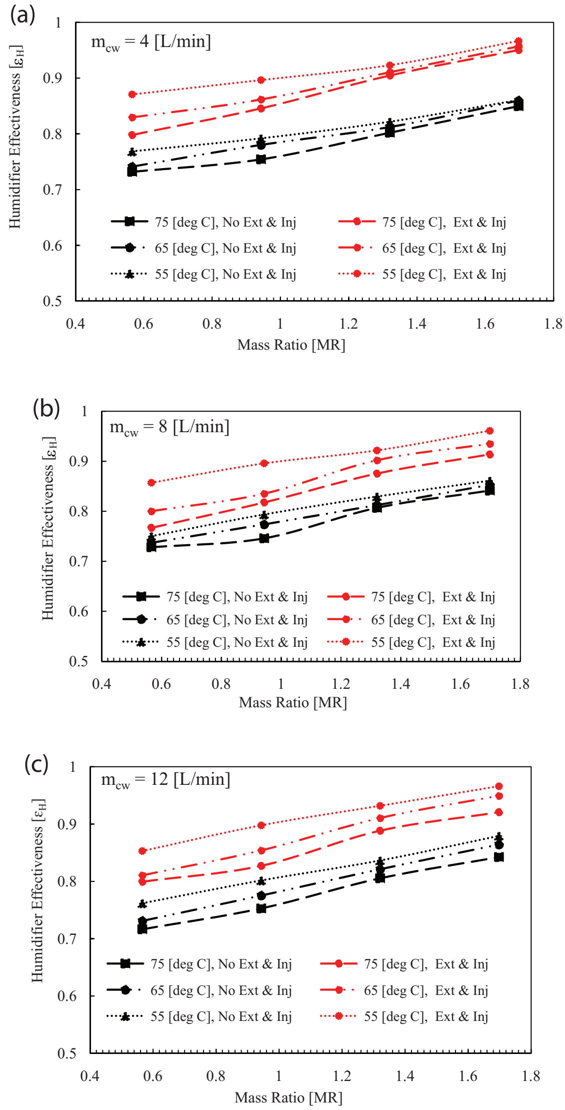

Fig. 6. Effect of mass ratio on humidifier effectiveness at different hot water temperature with and without mass extractions and injections. (a) m_{cw} = 4 L/min, (b) m_{cw} = 8 L/min, and (c) m_{cw} = 12 L/min.

temperature since the driving force for the heat and mass transfer processes increases with the water temperature. In other word, higher dehumidifier effectiveness will leads to effective pre-heating, and consequently higher TBT [31].

For the baseline case, the maximum and minimum humidifier effectiveness are 88% and 72%, respectively, as presented in Figs. 6(a)–(c), while that for dehumidifier, effectiveness are 97% and 90%, respectively, as depicted in Figs. 7(a)–(c). It is important to note that it is not practically possible to achieve 100% effectiveness since we may encounter temperature crossovers between the streams, which would violate the Second Law. The above component effectiveness values show that dehumidifier is more effective than the humidifier. To demonstrate the impact of mass balance on components effectiveness, let us look at Fig. 6(c). The maximum (87.9%) and minimum (71.65%) humidifier effectiveness are raised by about 10% and 12%, respectively, through

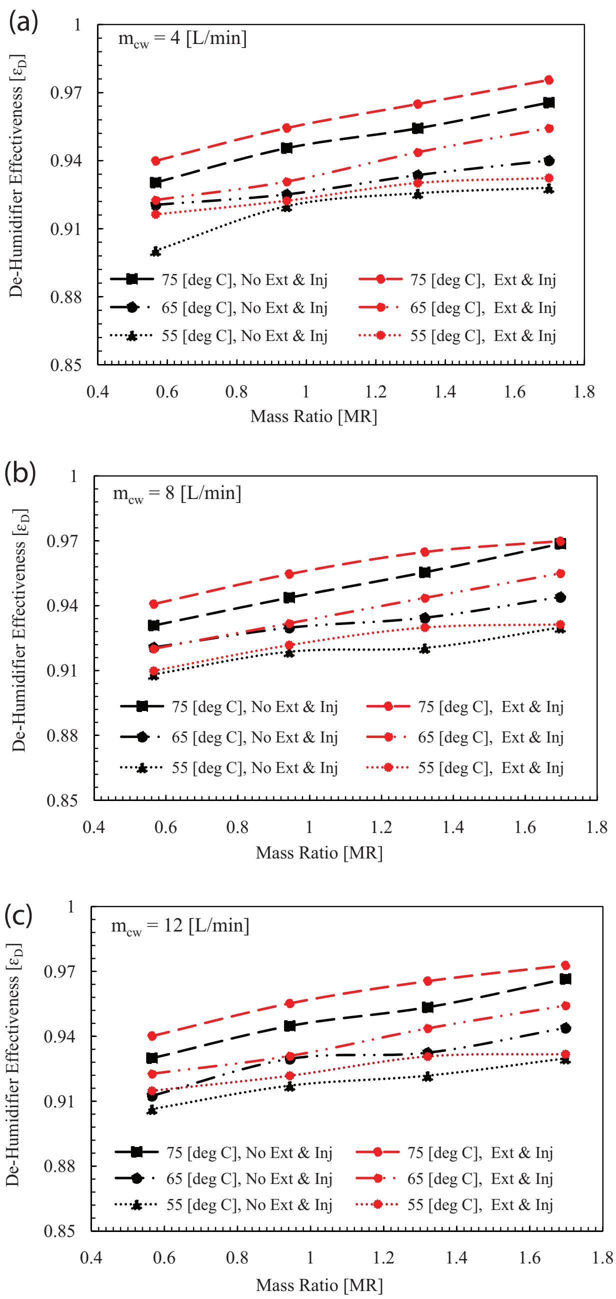

Fig. 7. Impact of mass ratio on dehumidifier effectiveness at different hot water temperature with and without mass extractions and injections. (a) m_{cw} = 4 L/min, (b) m_{cw} = 8 L/min, and (c) m_{cw} = 12 L/min.

mass balancing. Similarly, the maximum (96.55%) and minimum (90%) dehumidifier effectiveness are elevated by about 1% and 2%, respectively, via mass balancing as illustrated in Fig. 7(a). The improvements in the component effectiveness may be due to the fact that stream extractions and injections can result in a more uniform distribution of the driving forces across the system, which further reduces irreversibility. In a heat and mass exchanger, such as a humidifier or dehumidifier, there are two driving forces, temperature difference and concentration difference [32]. During humidification process and dehumidification process, the driving force is the difference between the bulk moist-air vapor concentration and the vapor concentration at the liquid interface. Balancing the stream in the system reduces the concentration differences that drive mass transfer along the length of the humidifier and the dehumidifier, thereby improving the component effectiveness.

Table 1
Uncertainty values of experimental results

Calculated parameters	Uncertainty value (δ_R)
Air density	0.004311 (kg/m^3)
Air mass flow rate	2.496 × 10^{-5} (kg/s)
Mass ratio (MR)	0.005702
Productivity	1.2 × 10^{-4} (L/min)
Recovery ratio (RR)	2.503 × 10^{-5} °C
Heat input ($\dot{Q}$)	1.12 (W)
Gain output ratio (GOR)	0.000454

3.2. Uncertainty analysis

The uncertainty is estimated in the calculated results based on the uncertainty in the primary measurement [33]. The results (R) is a function of independent variables ($x_1, x_2, \ldots x_n$). Kline and McClintock [34] developed a method to calculate the bias error of calculated variables. If the uncertainty in the independent variables are all given with the same odds, then the uncertainty in the result having these odds are:

$$\delta_R = \left[\left(\frac{\partial R}{\partial x_1}\delta_1\right)^2 + \left(\frac{\partial R}{\partial x_2}\delta_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\delta_n\right)^2\right]^{1/2} \quad (4)$$

where δ_R is the uncertainty of result R.

Uncertainties of calculated parameters such as RR, GOR, productivity, and mass ratio are based on the uncertainties in the measured parameters. Using the above formulation and the ranges provided by the supplier, the uncertainty values for the results are tabulated in Table 1.

4. Conclusions

This study has experimentally examined the impacts of stream extractions from one component and injections into the other component of a cross-flow packed-bed HDH system, with the aim of enhancing the system performance through reduction of system irreversibilities. The system productivity, gained output ratio, RR and components effectiveness of an open-air closed-water heated cross-flow packed-bed HDH cycles were analyzed, both with and without mass extractions/injections, and the following major conclusions can be drawn from the study:

- The rate of fresh water production, GOR, and component effectiveness improve as the feed water flow rate, that is, mass flow rate ratio (MR) increases, due to the promotion of flow turbulence level in the packing beds that increases the fluid heat transfer coefficient resulting in a higher vapor generations. However, RR of the system was found to decrease with increasing MR, because mass flow of feed per unit mass of air decreases at a faster rate than the mass flow of product water per unit mass of air.

- There is an improvement in the system productivity, RR, and the dehumidifier effectiveness, as the temperature range of the cycle increases, that is, as the feed temperature (TBT) increases. On the other hand, increasing the TBT decreases the GOR and the humidifier effectiveness of the system.
- The highest GOR of the system without mass extractions/injections is limited to approximately 1.6, and it is approximately 2.7 for the system with mass balancing.
- The top system productivity without mass balancing is about 138 L/d and about 144 L/d with stream extractions and injections.
- The peak RR of the system without stream extractions/injections is limited to 1.14% and approximately 1.33% for the system with mass balancing, representing about 17% improvement over the baseline case.
- The maximum humidifier effectiveness for the system without mass balancing is approximately 88%, and this value was elevated by about 10% through stream extractions and injections.
- The influence of mass extractions and injections for the dehumidifier effectiveness is marginal over the baseline case.
- The effect of cold water flow rate on the system performance is non-significant as long as the minimum cold water flow rate required for the effective vapor condensation is maintained.
- In general, stream extractions and injections improve the performance of the built HDH system, as we recorded enhancement in GOR, rate of condensate, components effectiveness, and RR.

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