EXPERIMENTAL INVESTIGATIONS OF A CROSS-FLOW HUMIDIFICATION DEHUMIDIFICATION DESALINATION SYSTEM

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ABSTRACT

This paper presents the performance of a water heated, cross flow humidification dehumidification (HDH) desalination system with brine recirculation designed, constructed and operated in a controlled environment.The presented HDH units are easy to build, do not require sophisticated maintenance and are suitable for remote areas where high level of technical background is not abundant.The influence of mass ratio (MR) at different hot water temperature on Gain output ratio (GOR), Recovery ratio (RR), humidifier, and dehumidifier effectiveness is investigated. The system is operated at different hot water temperatures, hot water flow rate ranging from 60 – 75 ^{o}C, and 4 – 18 L/min, respectively. The obtained results show that the built system is capable of producing distillate water of about 92 Liters per day,a GOR of 1.3, and the components effectiveness ranges from 92 – 97% and 53 – 79% for dehumidifier and humidifier respectively.

Keywords: Humidification, dehumidification, HDH, Thermal desalination technology, Gained output ratio (GOR), Cross-flow, Experimental, Effectiveness.

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1 INTRODUCTION

As the global population rises, so does the demand for water, which puts pressure on the planet's finite freshwater supply. Utilizing seawater, or desalination would be a solutionfor this issue. The major drawbacks of this solution are the high-energy consumption and the cost. The most used desalination techniques are the multi-stage flash (MSF) and the reverse osmosis (RO). A relatively new process which mimics the natural water cycle is being investigated, namely, humidification dehumidification (HDH) desalination. Until now, this process is only suitable for small to medium scale applications but with huge potential for improvement.Unlike conventional desalination techniques, HDH systems could be operated with a wide range of raw water quality. In addition, it is comprised of simple and inexpensive components, which don't require complex maintenance. These features make it a convenient choice for developing countries with narrow access to fresh-water supply.

HDH systems are classified into air heated, water heated, and air-waterheated cycles. Anothercriterion used in classification is whether the cycle itself is opened or closed. Research is still ongoing inthearea of HDH systems to determine the parameter(s) that would substantially contribute to the productivity of the system, which will result in higher gained output ratio (GOR). Al-Enezi et al.[1] experimentally assessed the features of the humidification-dehumidification (HDH) desalination system with respect to some operating conditions. The range of hot water temperature and flow rate considered were 35-45 ^{o}C and 25-75 kg/h respectively while the flow rate of the cooling water maintained at 5.625 kg/h. They reported that the rate of water production greatly depends on the temperature of the hot water and that the productivity increases withanincrease in theflow rate of the air and decrease in temperature of the cooling water.Dai and Zhang[2] investigated a unit of solar desalination using HDH technique. The system performanceis reported to be strongly affected by some parameters such salt water inlet temperature and mass flow rate to the humidifier and the air mass flow rate. The thermal efficiency of the unit was stated to be above 80%.Amer et al.[3] experimentally investigatedclosed-air open-water (CAOW) HDH desalination unitusing different packing materials. They reported that at high water temperatures, the effect of forced air circulation is negligible while the system performance increases by increasing water temperature and flow rate. Similarly, Narayan et al.[4]examined a water heated, CAOW HDH unit by focusing on the effectiveness of mass transfer between the humidifier and the dehumidifier. They obtained a maximum production rate of 700 l/day and it was claimed that the top brine temperature needs to be maximized in order to achieve a higher GOR.Quite a number of investigation also showed that for a constant or steady energy input, the productivity rate decrease with increase in flow rate of feed water[5].

On the aspect of closed-water open-air (CWOA) cycles and effect of variation in air flow rate, Yamali and Solmus[6] experimentally studied the effect of the various system operating parameters on the performance of a solar desalination unit using HDH process withCWOA. They reported a substantial improvement in the system productivity when the initial temperature and flow rate of the feed water were increased. They also noted that the system productivity almost remains the same when theflow rate of the air is increased.Yıldırım and Solmus[7]reported that heating the water has main significance on fresh water production than heating the air because of thehigher heat capacity of water, in fact, heating the air does not yield any substantial improvement on fresh water production.Al-Hallaj et al.[8]investigated the effect of air flow rate on the system performance by testing two units of CAOW. They reported that at high temperatures, forced convection will not be as effective as it is in natural convection.Nafey et al. [9] reported that the effect of ambient temperature and wind speed on the system productivity is insignificant. Contrary to these, Chang et al. [10]performed an experimental study on a multi-effect solar HDH system and different parameters such as hot water temperature, water, and air flow rates were investigated. They reported higher performance at higher water and air flow rates with theproductivity of freshwater reaching 63.6 kg/h for 1000 kg/h of brackish water. The maximum GOR of the system was about 2.1.

Another parameter affecting the productivity rate reported in theliterature is the ratio of water to air flow rate. Orfi et al. [11] studied the features of a solar desalination system using HDH technique. They reported that there is an optimum mass flow rate ratio corresponding to a maximum fresh water product.Orfi et al. [12] developed a model to analyze a solar desalination system using HDH technique. The model was basedon heat and mass transfer balances in every unit of the system. They reported that daily productivity varies with the ratio of mass flow rate of the salt water and air.Mohamed and El-Minshawy[13] studied the effect of water to air flow rateratio. They obtained the maximum productivity of the system at a ratio of 1.5 to 2.5. It was also reported that increasing the hot water inlet temperature and decreasing the cooling water temperature increased the distilled water productivity.The thermodynamic analysis of several HDH cycles including water heated HDH cycle has been investigated by Narayan et al. [14]. They also indicated that there is an optimum mass flow rate ratio where the system GOR is maximized. They also discussed the effect of components effectiveness on the System GOR that turns to be significant. Narayan et al.[14] also considered Multi extraction as a means for improving system performance, and Muller Holst [15]. Sharqawy et al. [16] provided a step-by-step design methodology assisted by charts to build a HDH system to deliver a certain product flow rate with a way to specify the energy needed and both water and air flow rates needed for both a water heated and a modified air heating HDH systems.Al-Sulaiman et al. [17] experimentally assessed the performance of a bubble column humidifier operated by solar energy. The impact of the air superficial velocity, inlet water temperature, and inlet air relative humidity on the performance of the system were investigated. A numerical CFD investigation of HDHcycle was performed by Saeed et al.[18] to determine the performance of the system. They developed a computational model based on conservation equations ofmass,momentum, energyand species, for predicting the velocity, temperature and concentrationfields within the cavity as well as calculating the rate of water evaporating from the cavity hot side and condensingon its cold side.Recently, Sharqawy et al. [19] investigated experimentally the performance of a cross flow humidifier with one, two or three fill packing materials. The humidification capacity, saturation efficiency increase with water mass flow rate, inlet water temperature and packing volume. Zubair et al. [20] evaluated the cost and performance of solar driven humidification-dehumidification desalination system. The influence of solar driven humidifier and the dehumidifier effectiveness, and number of collectors on productivity and GOR of the system were investigated.

Many investigationshave been carried out on different configuration of HDH system. However, the performance of cross-flow HDH arrangement did not receive enough attention.To fully understand the performance of this kind of HDH configuration, more investigation is needed. Hence, the motivation for this work.It is worth mentioning that this study considered water heated, cross-flow CWOA cycle with constant air and cooling water flow rate.

2 SYSTEM DESCRIPTION AND EXPERIMENTAL SET-UP

2.1 Process Description

The schematic line diagram of the cross-flow water-heated HDH system is shown in Figure 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 returned 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 and humidified through its 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 cycle while the hot water flows through a closed loop (brine recirculation).

The description of the system as presented in figure 1 is as follows: Hot water leaves the tank at state (1) and pumped into sprayers placed above the packing material. The rejected water is then collected at the bottom of the humidifier and drawn back to the tank (2) to be recirculated. Air is blown into the humidifier (5) where it is heated and humidified, and then blown into the dehumidifier (6). The humidified air condensed and exits at the unit (7) after passing through the condensers in which cold water flows. Cold water enters the dehumidifier (3) and then collected at the sink (4). Desalinated water is collected at the bottom of the dehumidifier (8) 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 (60, 70, & 75) ^{o}C and (4, 6, 8, 12 & 18) L/min respectively. While the cold water temperature and flow rate was kept constant at 30 ^{o}C ± 2 ^{o}C and 4 L/min ± 0.5 L/min respectively.

2.2 Experimental setup

The humidifier and dehumidifier units are made of Plexiglas 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 x 30 cm and a length of 90 cm. Three structured-typeplastic 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 at the humidifier entrance. The hot brackish water tank is fitted with two electric heaters of each having a heating capacity of 2 kW.The hot water tank is insulated to reduce heat loss and ensure steady and constant temperature. Both hot and cold water were pumped through the humidifier and dehumidifier respectively using small centrifugal pumps.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 was wrapped by a wet wick supplied by water from a gravity feeding syringes. Water flow rates are measured using In-line Flow meters glass tube rotameter (Omega FL46300) of ±5% accuracy and a range of 4-36 L/min. The air velocity is measured at the dehumidifier exit, and its measured using a digital anemometer (Smart Sensor AR 836) of ±3% accuracy.

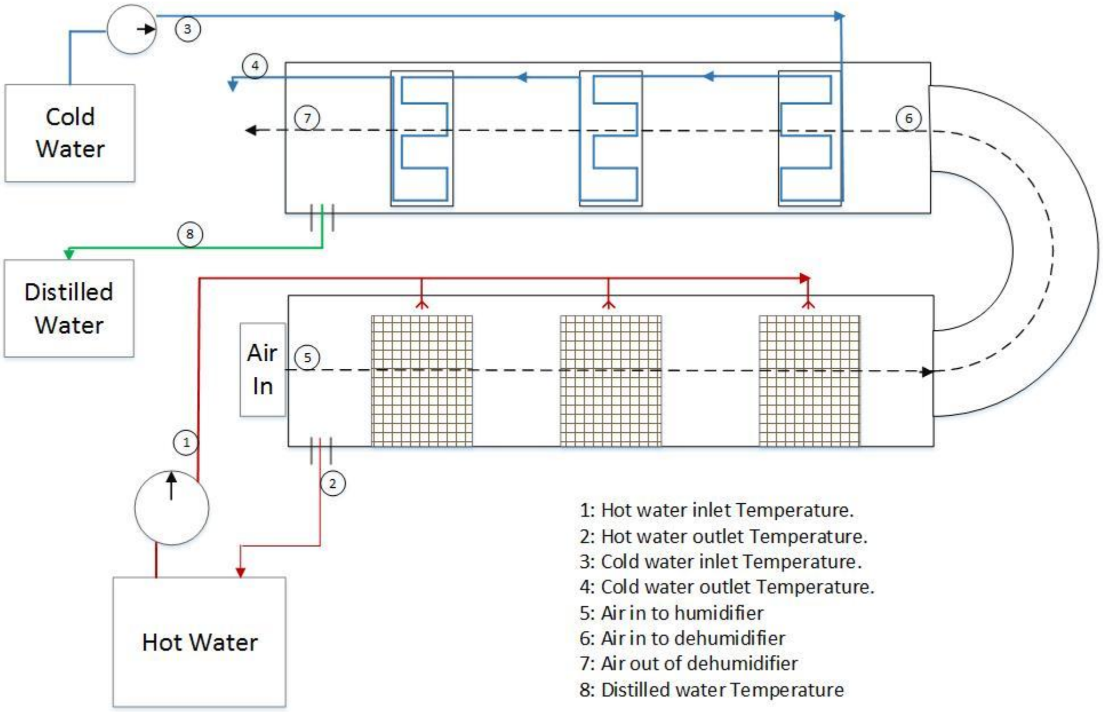

Figure 1. Schematic diagram of the experimental setup

2.3 Uncertainty Analysis

Based on the accuracy of each measuring instrument, an estimate ofthe uncertainty in measurements has been carried out according to theprocedure explained by Kline and McClintock [21]. According to Kline and McClintock, if the uncertainty in the independent variables are allgiven with the same odds, then the uncertainty in the result having these odds are:

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

Where δ_R is the uncertainty of result R.

Experimentaluncertainty errors in parameters such as recovery ratio (RR), gain output ratio (GOR), productivity and mass ratio are calculated based on the uncertainties in the measured parameters. Using the above equation and the instrument ranges provided by the supplier, the uncertainty values for the system performance parameters are estimated andsummarize in Table 2 of the results and discussion section.

3 RESULTS AND DISCUSSION

3.1 Comparison with previous work

To the best of the Authors knowledge, we have not encountered a cross flow HDH unit in the open literature. This was a motive to carry out this study. The early work of Nafey et al. [22] included a cross flow dehumidifier subjected to solar energy with maximum productivity of10.25 kg/day where solar radiation reached the peak hour of the day. The work of Yamali and Sulmus [6] is an experimental work with both air and water heating modes. The air heater is a solar collector. The productivity of the system is limited to about 1.1 kg/h at maximum water temperature of 50^{o}C.Other selected previous work on the productivity of HDH system is summarize in Table 1. It is worth mentioning that this workis intended to be used as a benchmark for similar experiment (cross flow HDH desalination system) as well as theoretical models.

Table 1.Selected previous works on HDH desalination system

Top system Temperature [^{o}C]	Feed water flowrates	Air flow rate	Maximum productivity	References
35 - 45	75 kg/h	5:10 nm^3/h	7.6 kg/day	[1]
50 - 85	0.856:2.772 kg/min	-	5.8 kg/hr	[3]
35.5 - 50	0.085:0.115 kg/s	0.045 - 0.068 kg/s	1.1 kg/h	[6]
25.94 - 36.75	0.005:0.045 kg/s	0.0049-0.0294 kg/s	10.25 kg/day	[22]
71 - 78	-	0.005 - 0.03 kg/s	7.8 kg/day	[23]
68.9 - 44.6	0.012-0.023 kg/s	0.004 - 0.0043 kg/s	1.45 kg/hr	[24]
5 - 35	0.4:1.4 kg/s	0.4-1.2 kg/s	27 kg/hr	[25]
60 -75	0.2 kg/s	0.177kg/s	92 kg/day	Current

3.2 Experimental Results

The performance of the cross flow HDH system is evaluated by calculating the GOR, amount of distillate collected, Recovery ratio, and humidifier and dehumidifier effectiveness. The mass ratio (MR) is obtained by varying the hot water flowrate while keeping the inlet air supply constant. Mass flow rate ratio is defined as ratio of the feed water to air mass flow rates. It is important to mention that the components effectiveness are given for the humidifier and dehumidifier [14, 16, 19, 26, 27], respectively as:

$$\varepsilon_h = max\left(\frac{\Delta H_w}{\Delta H_{max,w}}, \frac{\Delta H_a}{\Delta H_{max,a}}\right) = max\left(\frac{\dot{m}_{w,in}h_{w,in} - \dot{m}_{w,out}h_{w,out}}{\dot{m}_{w,in}h_{w,in} - \dot{m}_{w,out}h_{w,out}^{ideal}}, \frac{\dot{m}_a h_{a,out} - \dot{m}_a h_{a,in}}{\dot{m}_a h_{a,out}^{ideal} - \dot{m}_a h_{a,in}}\right) \tag{2}$$

$$\varepsilon_d = max\left(\frac{\Delta H_w}{\Delta H_{max,w}}, \frac{\Delta H_a}{\Delta H_{max,a}}\right) = max\left(\frac{\dot{m}_{w,out}h_{w,out} - \dot{m}_{w,in}h_{w,in}}{\dot{m}_{w,out}h_{w,out}^{ideal} - \dot{m}_{w,in}h_{w,in}}, \frac{\dot{m}_a h_{a,in} - \dot{m}_a h_{a,out}}{\dot{m}_a h_{a,in} - \dot{m}_a h_{a,out}^{ideal}}\right) \tag{3}$$

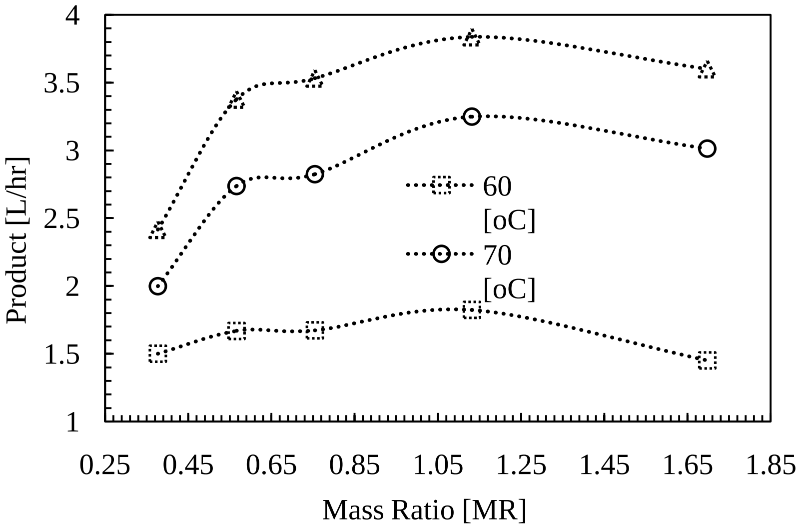

Figure 2. Effect of hot water temperature and water to air mass ratio on the productivity of thesystem.

Figure 2 shows the influence of increasing MR on the condensate collected. It can be observed that the system productivity increases with increasing MR. however, a maximum system product was reached at MR of 1.13, where further increment in MR resulted in decrement in the system productivity. This is as a result of the amount of hot water flow is much greater than the supplied air, leading to flooding of the system, thereby bring down the performance of the system. We also observed that at higher flowrate, more than half of the supplied water do not pass through one of the packing material. This is an indication that there is not enough surface area for water evaporation and may lead to reduction in system productivity. The productivity of the system also increases as the hot water inlet temperature increased. This is due to the greater water evaporation rate at higher temperature.

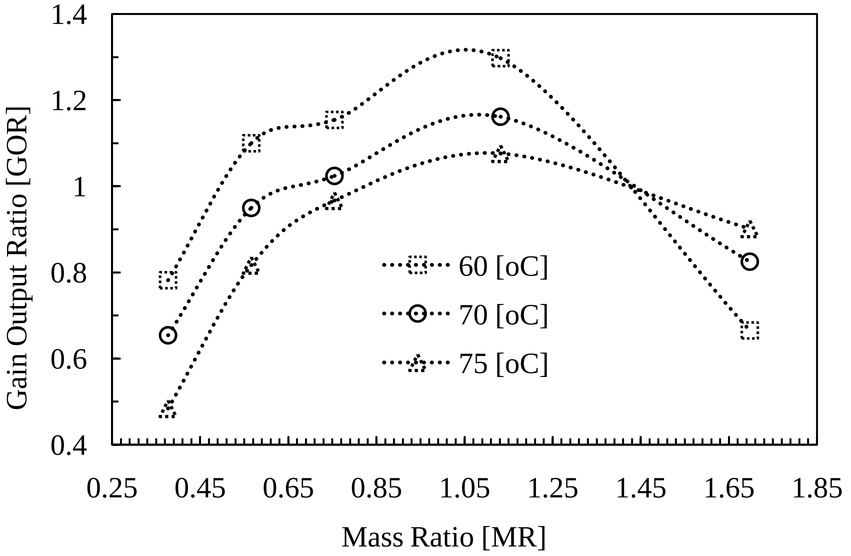

Figure 3. Effect of hot water temperature and water to air mass ratio on the gained output ratio GOR.

Presented in figure 3 is the effect of MR on GOR of the system, at different hot water temperatures. The GOR of the system is noticed to increase with increasing MR and decreases with increasing hot water temperature. This is expected, since at higher water temperatures, higher amount of energy is required, which is inversely proportional to the GOR of the system. The optimum MR that yield a maximum GOR of 1.3 was found to be 1.13. The optimum mass-flow rate ratio guarantees that the right amount of water is sprayed in the humidifierso that air is humidified to the extent needed as per the humidifier effectiveness. The result presented in figure 3 also suggests that the lower the hot water temperature, the better the GOR of the system. This however contradict the results illustrated in figure 2 that suggested higher temperatures to higher productivity. The conclusion that can be inferred from the two figures is to operate the system at higher temperature when we are concerned with productivity, and at low temperature when there is energy shortage.

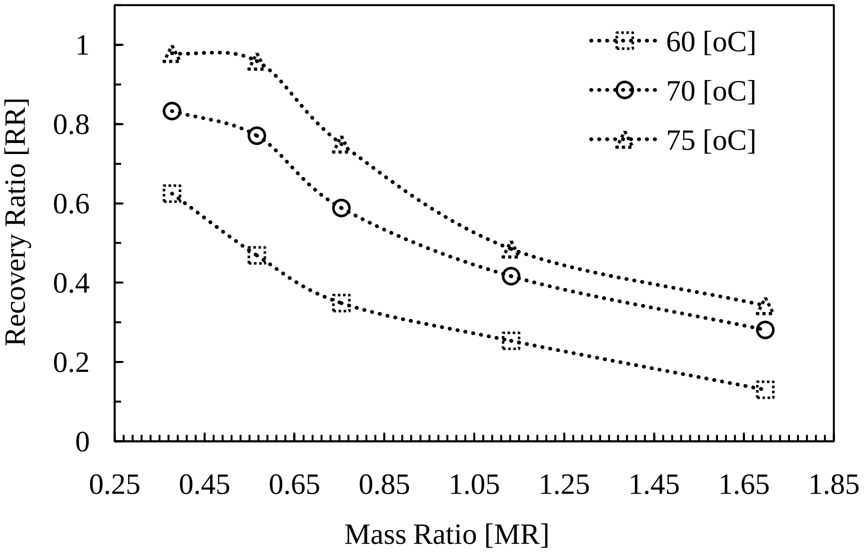

Figure 4. Effect of hot water temperature and water to air mass ratio on the recovery ratio (RR).

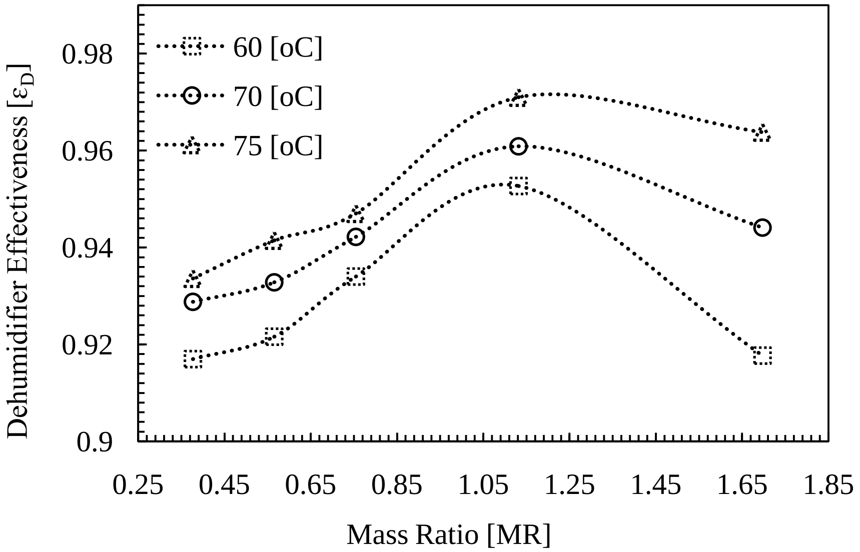

Figure 5. Effect of hot water temperature and water to air mass ratio on the dehumidifier effectiveness (ε_D).

Illustrated in figure 4 is the impact of hot water inlet temperatures and mass ratio (MR) on the recovery ratio (RR). Recovery ratio is defined as the ratio of fresh water produced to the inlet feed water. The RR decreases with increase in MR, and increase with increase in feed water temperature. This is an indication that less amount of fresh water is produced per feed water.

The increase in RR as a result of increase in hot water temperature is due to the higher evaporation of feed water thus, producing more fresh water for the same amount of feed water.

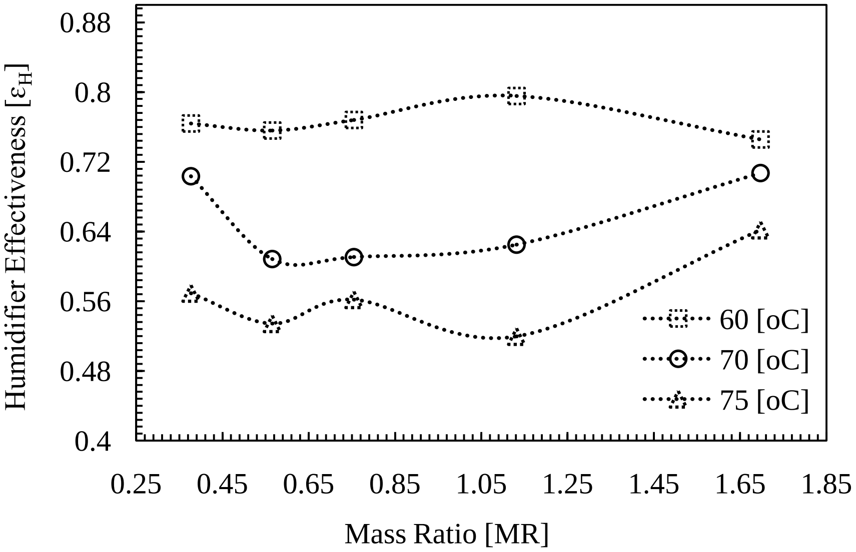

Figure 6. Effect of hot water temperature and water to air mass ratio on the humidifier effectiveness (ε_H).

Figure 5 and Figure ***6*** show the variation of water inlet temperatures and water to air mass ratio (MR) on the effectiveness of dehumidifier and humidifier respectively (refer to equations 2 and 3 for the definitions). The effectiveness of the humidifier and dehumidifier is defined as the maximum of either, water-side effectiveness or the air-side effectiveness. The effectiveness of dehumidifier is noticed to increase with *MR* and approaches unity at higher *MR* values, and then show a decreasing trend after the optimum MR of 1.13 is reached. Increasing MR is an indication of more water circulation, thus higher effectiveness is noticed. Figure 5 also shows that the effectiveness of dehumidifier increases with the water inlet temperature. This is due to the fact that the humidified air is better condensed at higher temperature, since there is better exchange of heat between the condenser and the humidified air. Effectiveness of the humidifier is shown to be better at lower inlet water temperature since the maximum value is harder to reach at high inlet temperature. There is no clear pattern taken by variation MR with humidifier effectiveness. This indicates that further parameters are expected to play a role in the humidifier effectiveness such as the number of transfer units, and the heat capacity ratio.

Table 2. Uncertainty values of experimental results.

Calculated parameters	Uncertainty Value (δ_R)
Air density	0.004311 [kg/m^3]
Air mass flowrate	2.496 x 10^{-5} [kg/s]
Mass Ratio (MR)	0.005702 [-]
Productivity	1.2 x 10^{-4} [L/min]
Recovery Ratio (RR)	2.503 x 10^{-5} [-]°C
Heat input ($\dot{Q}$)	1.12 [W]
Gain Output Ratio (GOR)	0.000454 [-]

CONCLUSIONS

The major conclusions from this work can be summarized as follows:

- Higher maximum temperature results in higher productivity, recovery ratio, and the effectiveness of the dehumidifier of the system.
- Increasing the feed temperatures decreases both the gain output ratio, and the humidifier effectiveness of the system.
- Increasing the mass ratio increases the productivity, gain output ratio, and the dehumidifier effectiveness of the system. An optimum MR at which further increase in MR leads to decrease in system productivity, GOR and effectiveness of the dehumidifier.
- Increasing the mass ratio decreases the recovery ratio of the system.
- The optimum mass flow rate ratio is 1.12 and the highest GOR obtained for the given conditions is about 1.3.

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