

EXPERIMENTAL INVESTIGATIONS OF THE PERFORMANCE 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 °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.

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 solution for 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-water heated cycles. Another criterion used in classification is whether the cycle itself is opened or closed. Research is still ongoing in the area 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 °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 with an increase in the flow 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 performance is 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 investigated closed-air open-water (CAOW) HDH desalination unit using 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 with CWOA. 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 the flow rate of the air is increased. Yildirim and Solmus[7] reported that heating the water has main significance on fresh water production than heating the air because of the higher 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 the productivity 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 the literature 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 based on 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 rate ratio. 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 HDH cycle was performed by Saeed et al. [18] to determine the performance of the system. They developed a computational model based on conservation equations of mass, momentum, energy and species, for predicting the velocity, temperature and concentration fields within the cavity as well as calculating the rate of water evaporating from the cavity hot side and condensing on 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 investigations have 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 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 EXPERIMENTAL DESCRIPTION

The system is mainly comprised of a humidifier (evaporator), dehumidifier (condenser), air blower, cold water source, and hot water tank as shown in

Figure 1. Both humidifier and dehumidifier units are made of horizontal rectangular ducts connected with U-pipe at one end. The other end of the humidifier is connected to the air blower, the hot brackish water tank is fitted with two electric heaters situated beneath the humidifier unit. The tank is insulated to reduce heat loss and ensure steady and constant temperature for a reasonable period of time and an electric pump is used to re-circulate the hot water through the humidifier. Thermocouples are attached to the strategic locations as shown in

Figure 1, it is important to note that both states 6 and 7 contained two thermocouples each to measure both dry and wet bulb temperature to determine the temperature and relative humidity of the air, respectively.

The three fluid loops considered are hot water closed-loop through the humidifier, cold water open-loop through the condensers, and air open-loop through the humidifier and the dehumidifier. Hot water leaves the tank at state (1) and 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). 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. Hot water temperature ranges from 60-75 °C with different hot water flow rates ranging from 4 – 18 L/min.

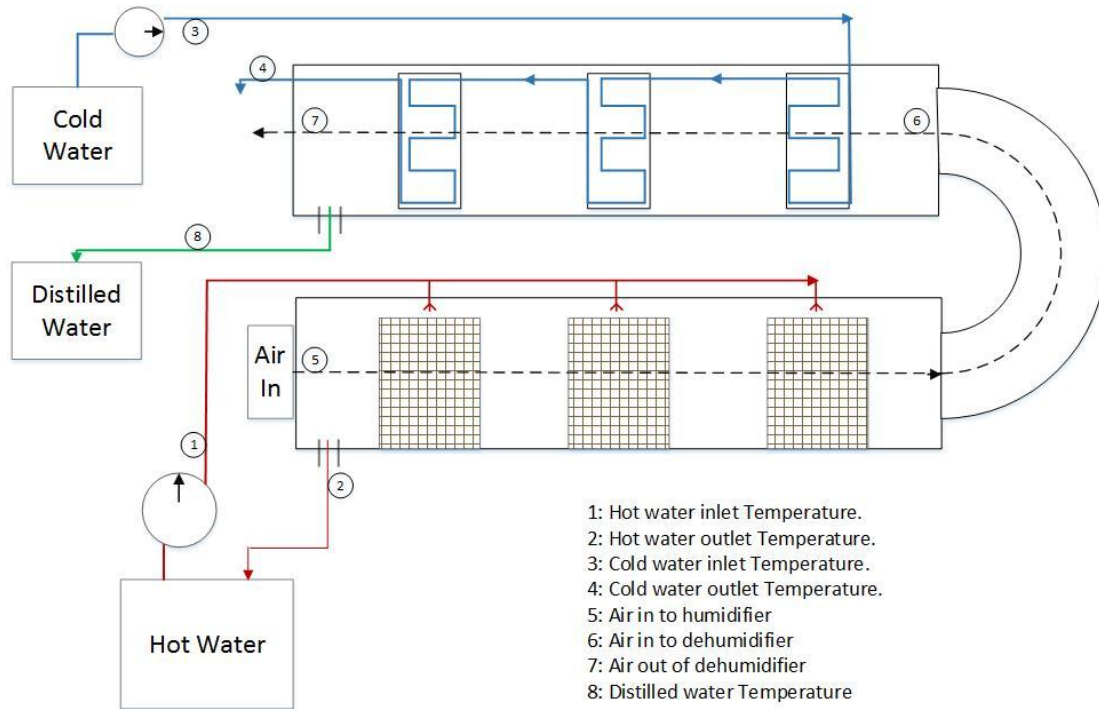


Figure 1. Schematic diagram of the experimental setup

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. Actually, this was a motive to carry out this study. The early work of Nafey et al. [21] included a cross flow dehumidifier subjected to solar energy with maximum productivity that does not exceed 1.2 kg/h where solar radiation reached the peak hour of the day. The work of Yamali and Sulmus [22] 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 4 kg/day at maximum water temperature of 45°C. However, the system under study produces 4 kg/h. It is intended that this work would be used as a benchmark for similar experimental as well as theoretical models.

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, 23, 24], respectively as:

$$\varepsilon_h = \max \left(\frac{\Delta H_w}{\Delta H_{max,w}}, \frac{\Delta H_a}{\Delta H_{max,a}} \right) = \max \left(\frac{\dot{m}_w h_{w,in} - \dot{m}_w h_{w,out}}{\dot{m}_w h_{w,in} - \dot{m}_w h_{w,out}^{ideal}}, \frac{\dot{m}_a h_{a,out} - \dot{m}_a h_{a,in}}{\dot{m}_a h_{a,out}^{ideal} - \dot{m}_a h_{a,in}} \right) \quad (1)$$

$$\begin{aligned} \varepsilon_d &= \max \left(\frac{\Delta H_w}{\Delta H_{max,w}}, \frac{\Delta H_a}{\Delta H_{max,a}} \right) \\ &= \max \left(\frac{\dot{m}_{w,out} h_{w,out} - \dot{m}_{w,in} h_{w,in}}{\dot{m}_{w,out} h_{w,out}^{ideal} - \dot{m}_{w,in} h_{w,in}}, \frac{\dot{m}_a h_{a,in} - \dot{m}_a h_{a,out}}{\dot{m}_a h_{a,in} - \dot{m}_a h_{a,out}^{ideal}} \right) \quad (2) \end{aligned}$$

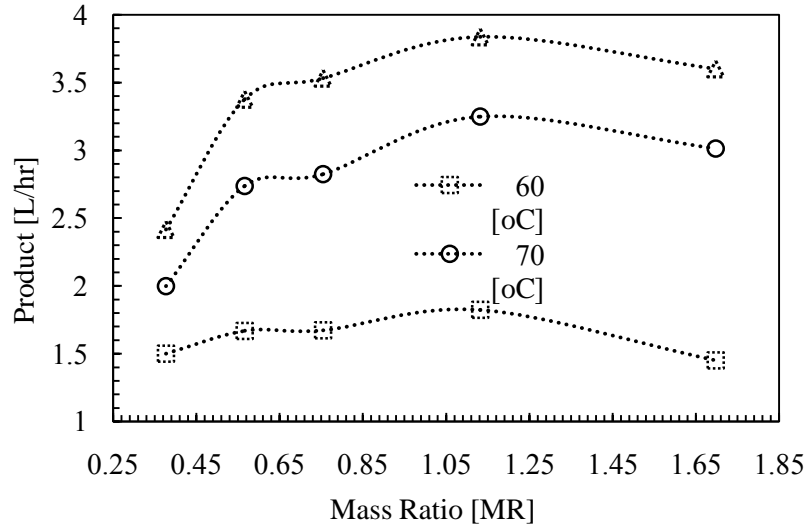


Figure 2. Effect of hot water temperature and water to air mass ratio on the productivity of the system.

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.

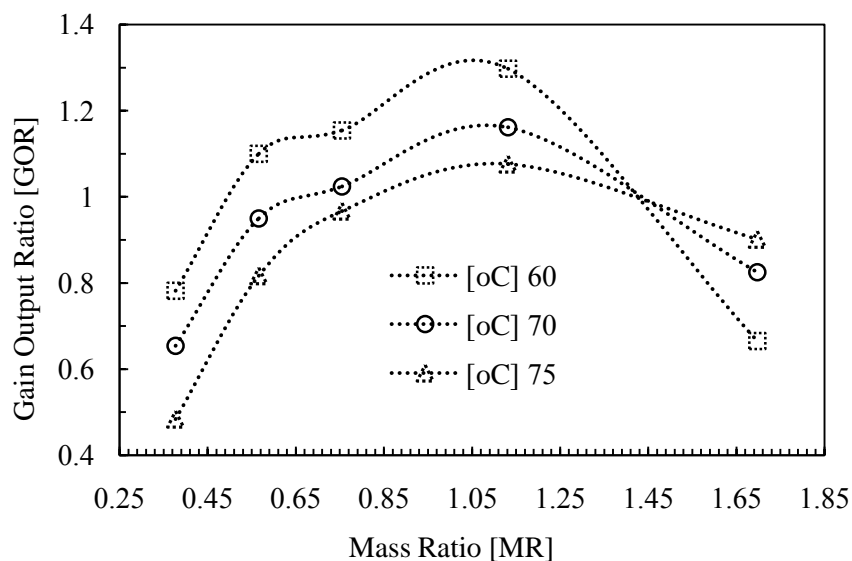


Figure 3. Effect of hot water temperature and water to air mass ratio on the gained output ratio GOR.

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 humidifier so 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.

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.

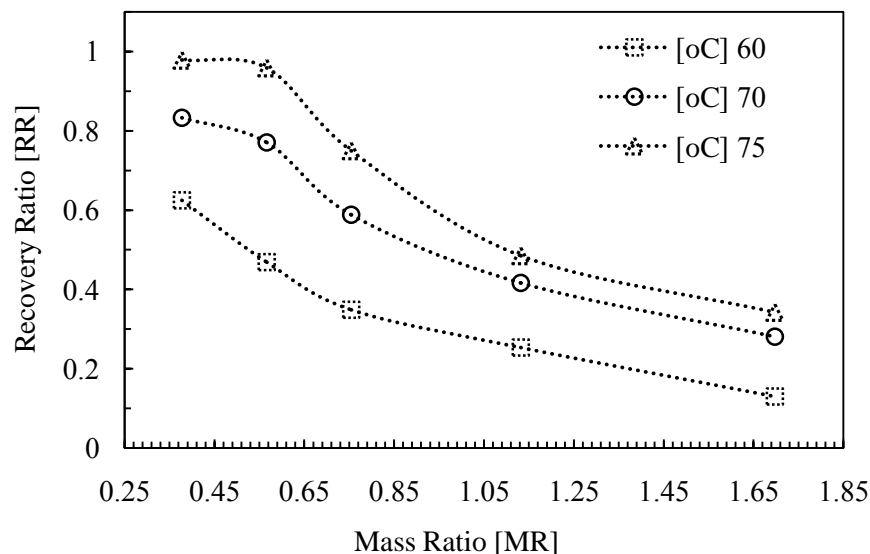


Figure 4. Effect of hot water temperature and water to air mass ratio on the recovery ratio (RR).

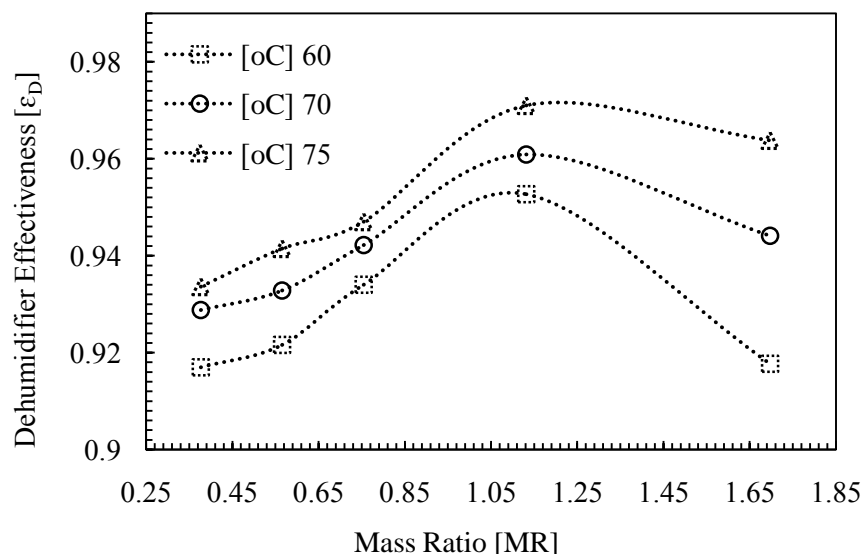


Figure 5. Effect of hot water temperature and water to air mass ratio on the dehumidifier effectiveness (ϵ_D).

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 1 and 2 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.

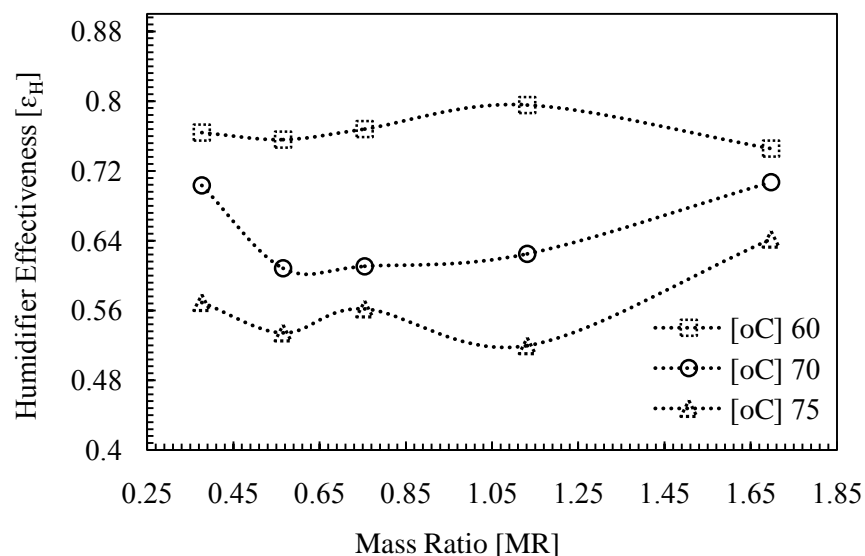


Figure 6. Effect of hot water temperature and water to air mass ratio on the humidifier effectiveness (ϵ_H).

4 CONCLUSIONS

The major conclusions of 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 till an optimum point, then they decrease.
- 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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