Enhancement of freshwater production of the seawater greenhouse condenser (Postprint)

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Abstract

Seawater greenhouse (SWGH) is a technology established to overcome issues related to open field cultivation in arid areas, such as the high ambient temperature and the shortage of freshwater. It adopts the humidification-dehumidification concept where evaporated moisture from a saline water source is condensed to produce freshwater within the greenhouse body. Various condenser designs are adopted to increase freshwater production in order to meet the irrigation demand. The aim of this study was to experimentally investigate the practicality of using the packed-type direct contact condenser in the SWGH to produce more freshwater at low costs, simple design and high efficiency, and to explore the impact of the manipulating six operational variables (inlet air temperature of the humidifier, air mass flowrate of the humidifier, inlet water temperature of the humidifier, water mass flowrate of the humidifier, inlet water temperature of the dehumidifier and water mass flowrate of the dehumidifier) on freshwater condensation rate. For this purpose, a direct contact condenser was designed and manufactured. Sixty-four full factorial experiments were conducted to study the effect of the six operational variables. Each variable was operated at two levels (high and low flowrate), and each experiment lasted for 10 min and followed by a 30-min waiting time. Results showed that freshwater production varied between 0.257 and 2.590 L for every 10 min. When using Minitab statistical software to investigate the significant variables that contributed to the maximum freshwater production, it was found that the inlet air temperature of the humidifier had the greatest influence, followed by the inlet water temperature of the humidifier; the former had a negative impact while the latter had a positive impact on freshwater production. The response optimizer tool revealed that the optimal combination of variables contributed to maximize freshwater production when all variables were in the high mode and the inlet air temperature of the humidifier was in

the low mode. The comparison between the old plastic condenser and the new proposed direct contact condenser showed that the latter can produce 75.9 times more freshwater at the same condenser volume.

Full Text

Preamble

Enhancement of Freshwater Production of the Seawater Greenhouse Condenser

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Abstract

The seawater greenhouse (SWGH) is an established technology designed to overcome challenges associated with open-field cultivation in arid regions, particularly high ambient temperatures and freshwater scarcity. Operating on the humidification-dehumidification principle, evaporated moisture from saline water sources is condensed within the greenhouse structure to produce freshwater. Various condenser designs have been adopted to increase freshwater production to meet irrigation demands. This study experimentally investigated the practicality of using a packed-type direct contact condenser in SWGH systems to achieve higher freshwater yields at low cost, with simple design and high efficiency, while exploring the impact of six operational variables: inlet air temperature of the humidifier, air mass flowrate of the humidifier, inlet water temperature of the humidifier, water mass flowrate of the humidifier, inlet water temperature of the dehumidifier, and water mass flowrate of the dehumidifier. A direct contact condenser was designed and manufactured for this purpose, and sixty-four full factorial experiments were conducted to examine these variables. Each variable was operated at two levels (high and low flowrate), with each experiment lasting 10 minutes followed by a 30-minute waiting period. Results showed freshwater production ranged between 0.257 and 2.590 L per 10-minute interval.

Statistical analysis using Minitab software identified the inlet air temperature of the humidifier as the most significant factor influencing freshwater production, followed by the inlet water temperature of the humidifier. The former exhibited a negative impact, while the latter showed a positive effect. The response optimizer tool revealed that maximum freshwater production was achieved when all variables were set to high mode except the inlet air temperature of the humidifier, which was set to low mode. Comparative analysis demonstrated that the new direct contact condenser produced 75.9 times more freshwater than the conventional plastic condenser at equivalent condenser volume.

Keywords: seawater greenhouse; humidification-dehumidification; direct contact condenser; freshwater production; water desalination

1. Introduction

The seawater greenhouse (SWGH) is an engineering technology developed to address challenges associated with open-field cultivation by creating favorable conditions for plant growth while simultaneously producing freshwater for irrigation. This technology is particularly suitable for hot, dry regions with poor water quality, including oil-field water, saline groundwater, surface water, and seawater. The SWGH operates as a desalination unit employing the humidification-dehumidification (HDH) approach, mimicking the natural hydrological cycle where evaporated water from saline sources is collected as freshwater after condensation.

A prototype SWGH was constructed in Oman in 2004, covering an area of 720 m^2. The system comprises two evaporative coolers and a condenser consisting of an array of 4,832 PVC tubes that vertically intercept the moist air stream. However, freshwater production of 300,000–600,000 L/d falls short of the irrigation demand (1,000,000 L/d) due to inefficiencies in the existing condensation unit. The condenser represents 20% of the total capital cost of the SWGH in Oman and requires frequent maintenance.

The overall efficiency of the SWGH is determined by condenser performance. Researchers have proposed several condenser designs and improvements, including plate channel condensers, passive condensers, vibrating plastic surface condensers, and direct contact condensers. Direct contact dehumidification (DCD) is an innovative process proposed to enhance SWGH condenser effectiveness and meet irrigation demands. The DCD system consists of two major components—a humidifier and a condenser—where moist hot air from the humidifier directly contacts cool freshwater in the dehumidifier for condensation. Direct contact condensers offer advantages over indirect contact designs, including simpler construction, lower investment costs, easier operation and maintenance, reduced heat transfer resistance due to large packing material surface area, lower pressure drop, higher water and energy recovery, and corrosion-free, leak-proof, durable materials.

In the packed-type DCD system, hot seawater from a solar heater is sprayed over packing material in the humidifier while relatively cold freshwater is recirculated in the dehumidifier. As moist hot air enters the dehumidifier and encounters cold freshwater, water vapor condenses directly on the packing material surface. Mass and heat transfer occurs from water to air in the humidifier and in the opposite direction in the dehumidifier.

Previous theoretical studies using finite difference simulation models have investigated DCD system performance, with polypropylene packing material (specific surface area of 320 m^2/m^3) in both humidifier and dehumidifier units. Simulation results indicated an optimal dehumidifier height of 0.65 m, beyond which an inversion area forms where evaporation occurs instead of condensation. The optimal air velocity into the HDH unit was calculated as 0.16 m/s for inlet water temperatures between 40.0°C and 60.0°C, with the DC condenser theoretically producing 6.0$×10^{3}$ to 22.0$×10^{3}$ L/(d · hm^2).

Multiple studies have identified key parameters affecting SWGH condenser performance, including inlet air temperature, air mass flowrate, inlet water temperature, and water mass flowrate for both humidifier and dehumidifier components. This study represents the first experimental trial of a packed-type DCD system for SWGH applications, investigating its capacity for low-cost, simple, high-efficiency freshwater production using operational data from the Oman SWGH facility.

2.1 Direct Contact Dehumidification (DCD) System and Experimental Design

The crossflow DCD system design was developed based on Zamen et al. (2013) and wind tunnel specifications described by Liao and Chiu (2002). The system was assembled at the Agricultural Experiment Station of Sultan Qaboos University, Oman. Both humidifier and dehumidifier units were filled with cellulose pads measuring 0.6 m × 0.6 m × 0.6 m. Two acrylic water compartments placed atop each unit featured 2-mm diameter holes drilled in their bottoms to ensure uniform water seepage to the pads.

Temperature and humidity monitoring throughout the DCD system employed dual relative humidity and temperature sensors plus T-type thermocouples. Inlet, middle, and outlet relative humidity values were measured and recorded using a data logger at 2-second intervals, with data averaged every 10 seconds. Air speed through the condenser was measured using a digital anemometer, while freshwater volume was manually measured at each experiment' s conclusion using a graduated cylinder. Instrument technical specifications are provided in Table S1.

Water mass flowrate was controlled by pump capacity, while air mass flowrate varied with fan capacity. The air mass flowrate was determined by calculating the weighted average of air speeds measured at four circular sections of the fan inlet. Volumetric flowrate was computed by multiplying each circle' s area by its corresponding air speed, with mass flowrate subsequently derived using air density. Zamen et al. (2013) reported an optimal air velocity of 0.16 m/s for maximum freshwater production, a value falling between the high (0.27 m/s) and low (0.11 m/s) velocities used in this experiment.

Hot and cold water mass flowrates were manually measured using a 5 L bucket and stopwatch. Pumps operated at maximum capacity for high flowrates and half capacity for low flowrates. Measurements were repeated three times and averaged (Table 1). Variable values for water temperature, air temperature, and relative humidity were selected based on historical data from the Oman SWGH in 2005 (Figs. 4-6). Summer data were prioritized due to peak irrigation demands and unfavorable greenhouse cultivation conditions. Daily maximum and minimum values of weather and operating parameters were obtained and incorporated into the experimental design whenever possible.

Table 1 presents the high and low values for the six operational variables. Full factorial experiments combining high and low values of all six variables were conducted ($2^6 = 64$ combinations) as detailed in Table S2. This design enabled investigation of both individual variable effects and their interactions. All experiments were performed between 09:00 and 18:00 (LST) during summer 2019.

Initial trials operated for 30 minutes followed by a 30-minute waiting period. This was reduced to 15 minutes operation with 30 minutes waiting, and finally to 10 minutes operation with 30 minutes waiting. During 30- and 15-minute runs, dehumidifier cold water temperature exceeded the dew point temperature of incoming moist air, causing evaporation instead of condensation. However, during 10-minute intervals, cold water temperature remained below the dew point, enabling condensation. Therefore, the 10-minute operation interval was selected for all experiments. In operational SWGH systems, DC condensers can run continuously because cold water is continuously supplied from the first evaporative cooler, unlike these experiments where continuous cold water supply was unavailable.

2.2 Statistical Analyses

The gained output ratio (GOR) index evaluated HDH cycle performance relative to thermal energy consumption, comparing freshwater produced (mfresh, L) to steam consumed (msteam, L) as follows:

$$GOR = \frac{m_{fresh}}{m_{steam}}$$

Minitab statistical software investigated relationships among the six independent variables, their interactions, and effects on the dependent variable. Confidence level was set at 95% with significance level of 0.05. Regression analysis identified variables and interactions significantly contributing to freshwater production. Analysis of variance (ANOVA), coefficient of determination (R^2), regression coefficients, and factorial plots interpreted results. The response optimizer tool identified optimal experimental combinations for maximum freshwater production. A Pareto chart illustrated significant variables and interactions among the six factors.

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3. Results and Discussion

All experiments maintained dehumidifier temperature below the dew point temperature of moist air, confirming condensation feasibility. Freshwater production ranged between 0.257 and 2.590 L per 10-minute interval across all experiments, indicating that increasing DC condenser operating duration would enhance production when limiting factors remain constant. Detailed production data for all experiments are provided in Table S2.

Although Zamen et al. (2013) recommended a maximum dehumidifier height of 0.65 m, the maintained temperature gap between dew point and coolant temperature throughout the 10-minute experiments suggests potential for height increase. Further studies are needed to determine optimal dehumidifier height and its impact on freshwater production.

3.1 Statistical Analysis of the Experiments

Figure 7 presents the Pareto chart of significant variables and interactions ranked by decreasing significance level. The R^2 value of 0.651 indicates that significant variables and interactions accounted for 65.1% of variability in freshwater production, with adjusted R^2 of 0.620. Table 2 shows F-test and P-values for significant effects. The model F-test value of 21.60 demonstrates that selected independent variables contributed significantly to variance in freshwater production, indicating a robust overall model. Variables and interactions with $P < 0.05$ were considered to have significant effects.

Table 3 presents regression coefficients for effective variables and interactions. Coefficient values indicate the impact on freshwater production from a one-unit increase in each effect. Positive signs indicate direct proportionality, while negative signs indicate inverse relationships. Among significant variables, inlet hot water temperature of the humidifier positively impacted freshwater production, while inlet air temperature of the humidifier had a negative effect. Among interactions, five-way interactions negatively impacted production, whereas three-way interactions showed positive effects.

A one-unit increase in inlet air temperature of the humidifier decreased freshwater production by 0.400 L, attributed to the small temperature gradient between inlet air and hot water temperatures. Conversely, a one-unit increase in hot water temperature increased production by 0.140 L, as higher temperatures enhance water evaporation and transfer sensible and latent heat to the air, increasing air temperature and moisture content. This widens the temperature gap between incoming airflow and coolant, resulting in greater freshwater production.

In operational SWGH systems, inlet air temperature can be practically reduced by decreasing greenhouse length (wide and shallow design) or positioning the DC condenser closer to the first evaporative cooler. Previous studies confirm that shallow, wide SWGH configurations produce more freshwater than long, narrow designs. Inlet water temperature can be increased using solar water heaters with small-diameter pipes and extended heater pipe lengths.

Response optimizer analysis identified optimal combinations of the six independent variables to achieve the target of 1,000.000 L/d to meet current SWGH irrigation demand. The optimal configuration required all variables at high mode except inlet air temperature of the humidifier, which required low mode. Tables 4 and 5 present the optimization goals and optimal variable combinations for maximizing freshwater production.

Figure 8 illustrates the optimal experimental combination for producing the target 1,000.000 L/d. Graph slope indicates effect magnitude, while line direction shows positive or negative impact. Inlet air temperature of the humidifier exhibited strong negative effects, while all other variables showed significant positive impacts except air mass flowrate and hot water mass flowrate of the humidifier, which had relatively weak positive effects.

3.2 Effects of High and Low Levels of Each Variable on Freshwater Production

The full factorial design comprised 64 experiments, with half performed at high mode and half at low mode. Figure 9 summarizes the impact of high (denoted 1) and low (denoted -1) modes on mean freshwater production, which averaged approximately 1.180 L/10 min. Hot water temperature of the humidifier showed a relatively strong positive effect, while inlet air temperature of the humidifier demonstrated a strong negative effect. Mean freshwater production increased with higher hot water temperatures, as continuously supplying hotter water to the pads maintains the temperature gap between incoming airflow and hot water, thereby increasing production.

Conversely, mean freshwater production decreased rapidly as inlet air temperature of the humidifier increased. Maintaining a large temperature gap between incoming airflow and humidifier hot water is crucial for freshwater production. As inlet air temperature rises, this temperature gradient diminishes, reducing overall freshwater production.

3.3 Highest and Lowest Freshwater Production

The maximum freshwater production of 2.590 L per 10-minute interval occurred when hot water mass flowrate, air mass flowrate, and hot water temperature of the humidifier were at high levels, with low inlet air temperature of the humidifier and low cold water temperature of the dehumidifier. These conditions represented optimal settings for the two most significant variables, maximizing the temperature gap between incoming air and humidifier hot water.

The minimum production of 0.257 L/10 min occurred under conditions of high inlet air temperature, high air mass flowrate, high water mass flowrate of the humidifier, and high inlet water temperature of the dehumidifier. This combination represented the worst-case scenario among all 64 experiments, with all six variables at suboptimal levels, adversely impacting freshwater production. These findings align with previous studies.

An interactive psychrometric chart illustrated air property changes during maximum and minimum production experiments (Fig. 10). In the maximum production case, dry air entered the humidifier at 24.8°C, 44.2% relative humidity, and 0.0086 kg/kg humidity ratio (state point P1). Evaporation from the hot water cycle enriched the air, raising temperature, relative humidity, and humidity ratio to 38.5°C, 100.0%, and 0.0448 kg/kg, respectively (P2). As this moisture-rich hot air contacted cold water in the dehumidifier, condensation produced 2.590 L in 10 minutes. Outlet air properties were 35.8°C, 88.6% relative humidity, and 0.0337 kg/kg humidity ratio (P3). While theoretical condensation requires near 100% relative humidity at state points P2 and P3, the actual outlet relative humidity dropped to 88.6%. Key variables maximizing production included low inlet air temperature, low dehumidifier cold water temperature, high humidifier hot water temperature, and high hot water mass flowrate.

In the minimum production experiment, hot dry air entered at 26.3°C, 54.1% relative humidity, and 0.0116 kg/kg humidity ratio (P4). After the first evaporative cooler, these values increased to 30.9°C, 100.0%, and 0.0287 kg/kg (P5). Condensation yielded only 0.257 L/10 min, with outlet air at 29.0°C, 94.6% relative humidity, and 0.0242 kg/kg humidity ratio (P6). The air entering the dehumidifier (P5) had substantially less temperature and moisture content than in the maximum production case (P2), explaining the production difference.

In both experiments, outlet relative humidity remained below 100.0%. Theoretically, successful condensation requires state points P2/P3 (maximum production) and P5/P6 (minimum production) to remain on the saturation line. Outlet relative humidity could be increased by optimizing air mass flowrate and increasing cold water mass flowrate of the dehumidifier. Table 6 provides detailed moist-air properties for each state point.

The maximum production (2.590 L/10 min) correlated with a GOR of 2.32, while minimum production (0.257 L/10 min) corresponded to a GOR of 0.56. Both values exceeded the 0.53 reported by Xu et al. (2020) for another HDH cycle. Higher GOR values indicate lower steam consumption and reduced operating costs, demonstrating that the HDH cycle at maximum production is more economically efficient.

3.4 Comparison Among Three Seawater Greenhouse Condensers

The Oman SWGH employs a crossflow indirect contact condenser made of plastic pipes (1.9 m × 0.8 m × 15.0 m), producing approximately 300,000 L of freshwater in 14 hours. This complex design incorporates 4,832 plastic pipes and 604 manifolds, requiring continuous maintenance. Zamen et al. (2013) proposed a DC condenser (0.6 m × 0.6 m × 0.6 m) to produce 450,000 L/d based on simulation models. The current study developed a DC condenser with identical dehumidifier dimensions (0.6 m × 0.6 m × 0.6 m) that produced up to 2.590 L in 10 minutes (217.560 L/d).

Since Zamen et al. (2013) did not specify collection time intervals or experimental dates, we assumed 14 hours (June daytime length) for the 450,000 L/d maximum production rate for comparison purposes. Table 7 summarizes specifications for all three condensers. Based on freshwater production per unit condenser volume, the Zamen et al. (2013) DC condenser showed the highest theoretical production rate. However, this was based on unverified simulation results, and production occurred under different input variables for air mass flowrate, water temperatures, and flowrates.

Comparing the two experimental studies, the DC condenser produced 75.9 times more freshwater than the old plastic condenser for the same volume, demonstrating exceptional efficiency and promise for SWGH applications due to its compact size, simple design, and high production capacity. These advantages strongly recommend replacing existing plastic condensers in Oman SWGHs with DC condensers.

4. Conclusions

This study provided the first experimental evaluation of a packed-type DCD system for SWGH applications. Statistical analysis identified inlet air temperature and inlet water temperature of the humidifier as the most significant variables affecting freshwater production. Maximum production reached 2.590 L/10 min when hot water mass flowrate, air mass flowrate, and hot water temperature were high, while minimum production was 0.257 L/10 min under opposite conditions. GOR values of 2.32 and 0.56 for maximum and minimum production, respectively, indicate efficient operation at peak performance.

Dehumidifier height can potentially be increased since coolant temperature remained above inlet dew point temperature in all experiments. Comparison of high and low variable levels across 32 experiment pairs confirmed that inlet air temperature of the humidifier had the strongest negative impact, while hot water temperature of the humidifier had a strong positive effect. The new packed-type DCD system demonstrates superior efficiency, producing approximately 75.9 times more freshwater than conventional plastic condensers at equivalent volume.

Future research should investigate additional variables affecting DCD system performance across broader input ranges, optimize condenser height, and evaluate alternative packing materials, particularly locally available options.

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Appendix

Table S1. Technical specifications of instruments used in the study

Instrument	Model	Measurement Range	Accuracy
Digital anemometer	HHF-SD1, OMEGA, Taiwan	0.2–5.0 m/s	±(0.2 m/s + 1.5% of reading)
T-type thermocouple	TT-T-22-SLE-1000, OMEGA	0.0°C–260.0°C	$±$0.5°C or $±$0.4% of reading

Instrument	Model	Measurement Range	Accuracy
Relative humidity and temperature sensor	HMP155, VAISALA, Finland	0%-100% RH, -80.0°C-60.0°C	$±$2% RH, $±$0.2°C

Table S2. Freshwater production from all 64 experiments with high and low values of each variable

[Note: The original table data appears to be truncated or corrupted in the source material. A complete table would show all 64 experimental combinations and their measured production values.]

Note: Figure translations are in progress. See original paper for figures.

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