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Development of Humidification-Dehumidification Seawater Greenhouse Technology for Arid Coastal Regions

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Abstract
A thermodynamic simulation study was performed on the influence of greenhouse-related parameters on a desalination process that combines fresh water production using humidification-dehumidification with the growth of crops in a greenhouse system. Thermodynamic modeling has shown that the dimension of the greenhouse had the greatest overall effect on the water production and energy consumption. A wide shallow greenhouse, 200 m wide by 50 m deep gave 125 $m^3.d^{-1}$ of fresh water, compared to the worst-case scenario with the same area (50 m wide by 200 m deep), which gave 58 $m^3.d^{-1}$. The wide shallow greenhouse consumed 1.16 $kW.h.m^{-3}$, while the narrow deep structure consumed 5.02 $kW.h.m^{-3}$. The construction of a prototype system in the Arabian Gulf will be presented as well as optimization studies of this structure. The benefits of the development of the Seawater Greenhouse for coastal regions in the Latin American and Caribbean Region will be discussed.

Keywords
Desalination, agriculture, modeling, humidification-dehumidification, seawater greenhouse

1. Introduction

There is a growing realization in arid and non-arid countries that the long-term solution to the shortage of potable water lies in a coordinated approach involving water management, purification, and conservation (Goosen and Shayya, 1999). Solar desalination methods are well suited for the arid and sunny regions of the world as in the Arabian Peninsula (Trieb et al., 2002; Hamed et al., 1993; Kumar and Tiwari, 1998; Sablani et al., 2003; Goosen et al., 2000; Goosen et al., 2003). A variety of solar desalination devices have been developed. One of the more successful examples is the multiple-effect still. Latent heat of condensation is recovered, in two or more stages (generally referred to as multi-effects), so as to increase production of distillate water and improve system efficiency. It has become apparent that a key feature in improving overall thermal efficiency is the need to gain a better understanding of the thermodynamics behind the multiple use of the latent heat of condensation within a multi-effect humidification-dehumidification solar still (Al-Hallaj et al., 1998). Both efficiency and economics need to be considered when choosing a solar desalination system. While a system may be technically very efficient it may not be economic (i.e., the cost of water production may be too high) (Fath, 1998).

One example of a humidification-dehumidification system is a pilot plant built at Kuwait University (Delyannis and Belessiotis, 1999). This system consisted of a salt gradient solar pond, which was used to load the air with humidity. Fresh water was collected by cooling the air in a dehumidifying column. Khalid (1993) also described an air-dehumidification method suitable for coastal regions. In a similar study, a closed-air cycle humidification-dehumidification process was used by Al-Hallaj et al. (1998) for water desalination. Paton and Davies (1996) used the humidification-dehumidification method in a greenhouse-type structure for desalination and for crop growth (Figure 1). Their seawater-greenhouse, produced fresh water and crop cultivation in one unit. It was suitable for arid regions that have seawater nearby. The temperature differences between the solid surfaces heated by the sun and cold water drawn from below the sea surface was the driving force in the system. A controlled environment was provided inside the greenhouse. A thermodynamic model was employed in the analysis of water production and energy consumption (Davies et al., 2004).

The primary aim of our study was to determine the influence of greenhouse-related parameters on fresh water production using humidification-dehumidification with the growth of crops in a greenhouse system. A thermodynamic model was used based on heat and mass balances. The construction of a prototype system in the Arabian Gulf will be presented as well as optimization studies of this structure. The benefits of the development of the Seawater Greenhouse for coastal regions in the Latin American and Caribbean Region that are suffering from salt infected soils and shortages of potable groundwater will be discussed.

2. Methodology

2.1 Thermodynamic Simulation Model

The thermodynamics of the humidification-dehumidification Seawater Greenhouse system was modeled using a software program developed by Seawater Greenhouse Limited, UK. The computer program consisted of several modules: Seapipe, Airflow, Evaporator 1, Roof, Planting Area, Evaporator 2, and Condenser (air/water heat exchanger). Weather data for the year 1995 obtained from the Meteorological Office situated at Muscat were used. The software needs a weather data file and a bathymetric (seawater temperature) file. These are specific to a location.

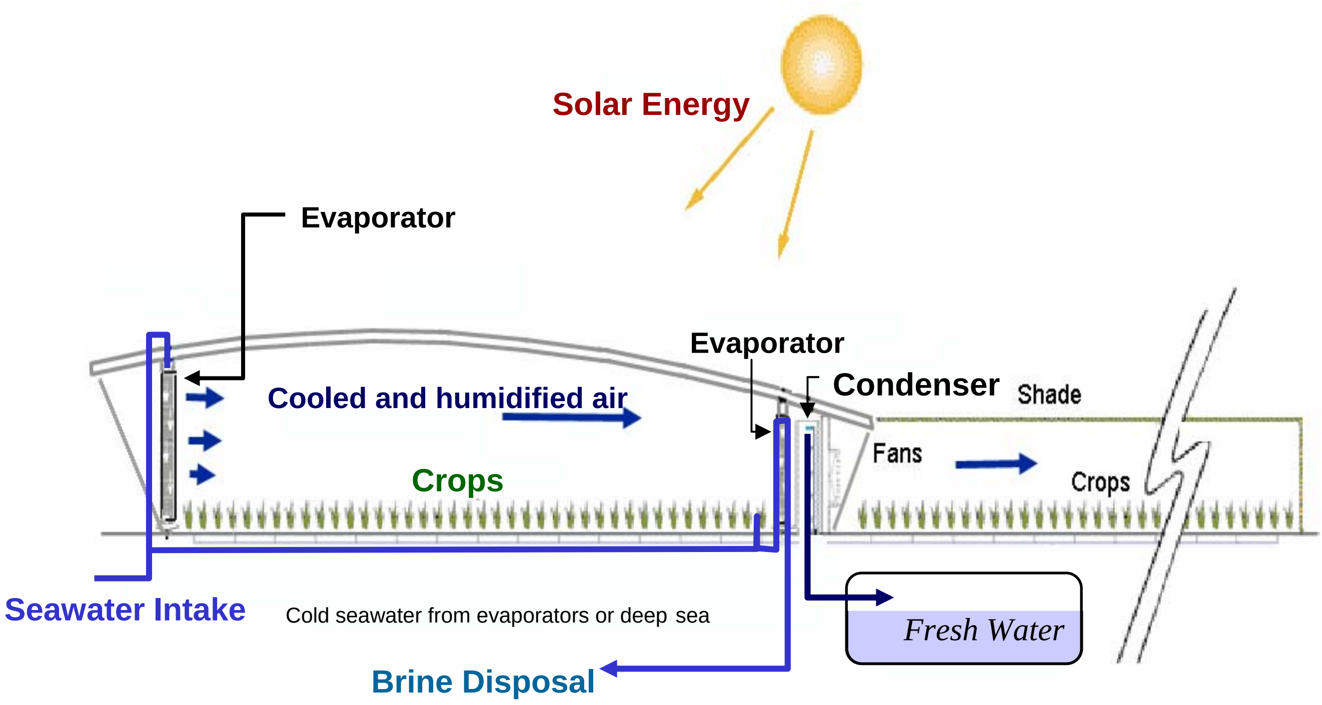

Figure 1. Seawater Greenhouse (Paton and Davies, 1996): 1. Surface seawater trickles down the front wall evaporator, through which air is drawn into the Greenhouse. Dust, salt spray, pollen and insects are trapped and filtered out leaving the air pure, humidified and cool; 2. Sunlight is selectively filtered by the roof elements to remove radiation that does not contribute to photosynthesis. This helps to keep the Greenhouse cool whilst allowing the crops to grow in high light conditions; 3. Air passes through a second seawater evaporator and is further humidified to saturation point; 4. Saturated air passes through the condenser, which is cooled using cold deep-sea water. Pure distilled water condenses and is piped to storage; 5. Fans draw the air through the Greenhouse and into the shade house area.

The file contained transient data on solar radiation on a horizontal surface, dry bulb temperature and relative humidity of air, wind speed, and wind direction. The bathymetric file contained temperature of the seawater at distance along the sea bed from the coast. The software program predicts the inside air conditions and water production for a given configuration/dimension of the greenhouse, and weather and bathymetric data. The program allows many parameters to be varied. These variables can be grouped into the following categories: greenhouse (i.e. dimension of the greenhouse and its orientation, roof transparency of each layer, height of front and rear evaporative pads, height of the planting area, and condenser), seawater pipe, and air exchange.

2.2 Simulation runs

In the present analysis three parameters (i.e., dimension of the greenhouse, roof transparency and height of the front evaporator) were taken as variables. These parameters were varied as follows: Dimensions of Greenhouse (width x length) with the area being kept constant at 10^4 m^2 (50 x 200, 80 x 125, 100 x 100, 125 x 80, and 200 m x 50 m); Roof Transparency (0.63 x 0.63 and 0.77 x 0.77); Height of the Front Evaporator (3 and 4 m). The parameters kept constant were: Height of Planting Area (4 m); Height of the Rear Evaporator (2 m); Height of the Condenser (2 m), Orientation of Greenhouse (40^o N); Seawater Pipe Diameter (0.9 m) and Length (5000 m); Volumetric Flow ($0.1 m^3.s^{-1}$); Pit Depth (-3 m), Height (7.5 m), and Wall Thickness (0.1 m); Air Change ($0.15\ min^{-1}$); and Fin Spacing (0.0025 m) and Depth (0.1506 m).

Three climatic scenarios were considered. In the *temperate version*, the temperature in the growing area is cool and the humidity high. This version is suited to crops such as lettuces, French beans, carrots, spinach, tomatoes, strawberries, and tree saplings. Many of these crops are normally difficult or impossible to grow in the hot, arid location considered. In the *tropical version*, the temperature in the growing area is warm and the humidity very high. Examples of suitable crops include aubergines, cucumbers, melons, pineapples, avocados, peppers, and pineapple. The design is similar to that of the *temperate version*, but the airflow is lower. The *oasis version* allows for a diversity of crops. This version is separated into temperate and tropical sections of equal area. The tropical area could be used for propagation of crops later grown in the temperate area. A double evaporator design makes it efficient in the production of fresh water. Air flows sequentially through the *temperate* and *tropical* sections. The areas covered by these greenhouses were 1080 m^2 (*temperate* and *tropical*) and 1530 m^2 (o*asis*).

2.3 Construction of Prototype System in Oman and Optimization

A 1000 m^2 Seawater Greenhouse was constructed at the Al-Hail site beside the ocean in Muscat, Oman. The system consisted of two sections to demonstrate the expandability of the Greenhouse to whatever size is required by the farmer/company. The cover consisted of standard plastic that is normally used for greenhouses. An array of pipes in the roof of the Seawater Greenhouse works as both a solar collector and a heat exchanger with the surrounding air. Since the air in the roof of the Greenhouse is generally hotter than ambient, the pipes can absorb heat and the apparent efficiency as a solar collector can exceed 100%.

During visits to the SQU Al-Hail Seawater Greenhouse in September and December observations were made using a Delta-T datalogger and hand-held instruments. These observations enabled the system to be characterized and modeled in detail, allowing for the optimization of the Greenhouse operation.

3. Results and Discussion

3.1 Simulation studies

Analyses showed that the dimensions of the greenhouse (i.e., width to length ratio) had the greatest overall effect on water production and energy consumption (Figures 2 and 3, respectively). The overall water production rate increased from 65 to 100 $m^3.d^{-1}$ when the width to length ratio increased from 0.25 to 4.00. Similarly the overall energy consumption rate decreased from 4.0 to 1.4 $kW.h.m^{-3}$ when the width to length ratio increased from 0.25 to 4.00.

A 5 x 2 x 3 full factorial design was employed with five dimensions (width and length) of greenhouse, two roof transparencies, and three heights of the front evaporator. A total of thirty simulation runs were carried out with one year of weather data. The water production and power consumption data were analyzed using the Statistical Analysis System (SAS) program. Analysis of variance (ANOVA) procedure was used to detect the significance of the dimension of the greenhouse, transparency of roof materials, and height of the front evaporator.

The results showed that the overall effects of roof transparency and evaporator height on water production were not significant. It was possible for a wide/shallow greenhouse (200 m wide by 50 m deep) with an evaporator height of 2 m, to give 125 $m^3.d^{-1}$ of fresh water. This was greater than a factor of two compared to the worst-case scenario with the same overall planting area (50 m wide by 200 m deep) and a similar evaporator height that produced 58 $m^3.d^{-1}$. For the same specific cases, low power consumption went hand-in-hand with high efficiency. The wide shallow greenhouse consumed 1.16 $kW.h.m^{-3}$, while the narrow deep structure consumed 5.02 $kW.h.m^{-3}$. While these results suggest that a wide/shallow greenhouse is technically the most efficient, it is important to remember that the model does not take into account the increase in capital and operating costs of the evaporator and condenser for the wider greenhouse.

3.2 Performance of Seawater Greenhouse for Various Climate Scenarios

Total fresh water production for the three climate scenarios was also calculated (Table 1). One year's detailed meteorological data from Seeb Airport, Muscat, was entered into the model to test the performance sensitivity for the various designs. The model results predicted that the Seawater Greenhouse would perform efficiently throughout the year, but with measurable variations in performance between the alternative versions. For example, the water production rate and energy efficiency results from the simulations using optimized and constant values for fan and pump speeds showed that the *temperate scenario* had almost double the water production rate per hectare compared to the *tropical scenario* (i.e., 20,370 $m^3.ha^{-1}$ compared to 11,574 $m^3.ha^{-1}$) while the power consumption for the former was only slightly higher (i.e., 1.9 and 1.6 $kW.h.m^{-3}$, respectively). Table 2 shows the performance at the optimum settings. Water productivity can be improved but with greater energy consumption, and efficiency can be improved but with a small reduction in water output. For example, the *oasis version* had the highest water production rate at 20,915 $m^3.ha^{-1}.yr^{-1}$, but at the cost of the highest energy consumption of 1.41 $kW.h.m^{-3}$**.**

3.3 Optimization of Air and Water Flows in SQU Al-Hail Seawater Greenhouse

Based on the observations taken from the Al-Hail greenhouse, some mathematical modelling was performed using an Excel spreadsheet. Unlike the modelling described above, this modelling does not take attempt to predict year-round performance. It is only intended to guide design improvements, in particular to determine optimal seawater and airflow rates entering the back evaporator. These parameters are very important to the overall performance.

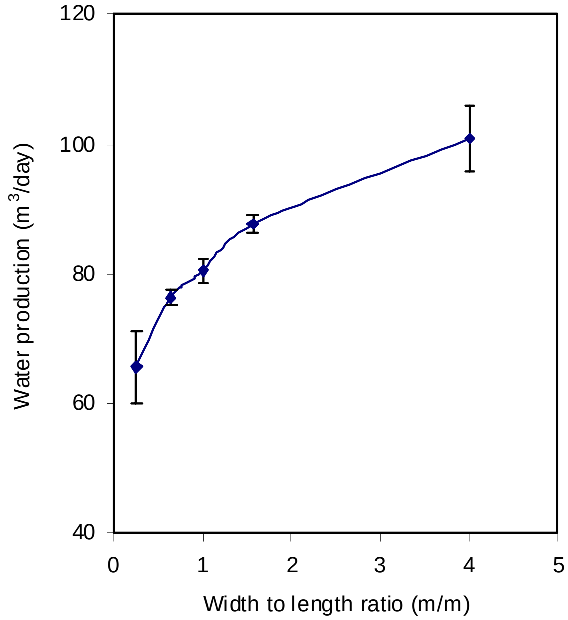

Figure 2. Overall effect of width to length ratio on water production rate (Sablani et al., 2003).

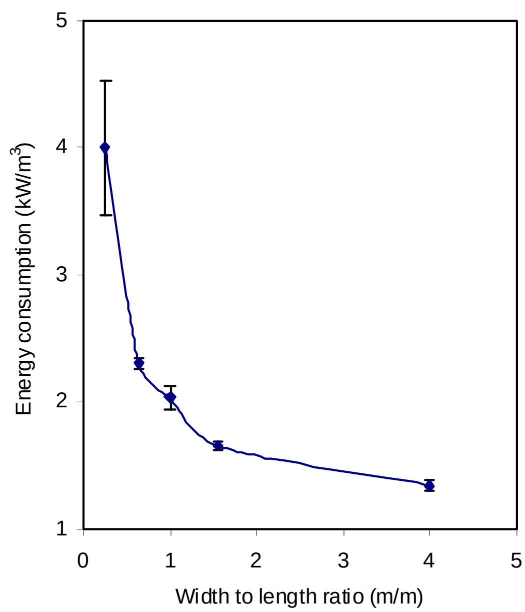

Figure 3. Overall effect of width to length ratio on energy consumption (Sablani et al., 2003).

Table 1. Performance of Seawater Greenhouse for Various Scenarios (Sablani et al., 2003).

	Total Fresh Water Produced ($m^3.ha^{-1}.yr^{-1}$)	Power Consumption ($kW.h.m^{-3}$)
Temperate	20370	1.9
Tropical	11574	1.6
Oasis	23529	2.3

Table 2. Seawater Greenhouse Performance at Optimum Settings (Sablani et al., 2003).

Model	Orientation (º)	Fan Gain	Pump Trigger	Product Water ($m^3.yr^{-1}$)	Product Water ($m^3.ha^{-1}.yr^{-1}$))	kW.h Used	$kWh.m^{-3}$
Temperate	50	0.14	0.2	2000	18519	2500	1.25
Tropical	50	0.14	0.2	1800	16667	1760	0.98
Oasis	50	0.14	0.2	3200	20915	4500	1.41

The modelling takes into account the solar pipes, back evaporator, and the condenser. The model of the condenser is 2-dimensional, considering the temperature variation both vertically and in the direction of airflow.

Ideally, the model should take into account the rise in temperature of the cooling water as it flows through the condenser. In practice, this is quite difficult to calculate as the air and water temperatures are coupled. Instead, the water is assumed to have a uniform temperature equal to the average of inlet and outlet. The output from the model is the mean temperature difference (air to water). This is used to assess the improvement in water output, which is assumed to increase proportionally. The baseline for the model is set to the conditions for 12.00 hrs on December 9, 2004 (a day for which a complete set of measurements was taken).

Baseline conditions:

Seawater flow in solar pipes	1.6 $kg.s^{-1}$	
Air flow into back evaporator	11.4 $kg.s^{-1}$	(=10.4 $m^3.s^{-1}$, 0.33 $m.s^{-1}$ at pad face).
Temperature difference air to water	1.4 ºC	

The precise optimum was found to be 4.7 $kg.s^{-1}$ of air (41% of the current flow) and 3.5 $kg.s^{-1}$ of water (2.2 times the current flow), yielding an improvement factor of 1.67 (Figure 4).

The optimum airflow was found to be between 4.3 and 4.7 $kg.s^{-1}$. This was about 40% of the original airflow of 11.4 $kg.s^{-1}$ when the Greenhouse was constructed. The optimum water flow was in the range 2.9 to 3.5 $kg.s^{-1}$, about twice the original water flow rate. Together, these optimisations gave an increase in water output of 1.67 times (i.e., 67% increase). Optimizing the water flow alone leads to a flow of 7 $kg.s^{-1}$ and an improvement factor of 1.38. Optimizing the airflow alone leads to a flow of 3.5 $kg.s^{-1}$ of air giving an improvement factor of 1.49 (based on the December case). Table 3 summarises some of the options for improving water output. The table shows that it is possible to double water output, in which case peak outputs of 1 $m^3.d^{-1}$ are achievable.

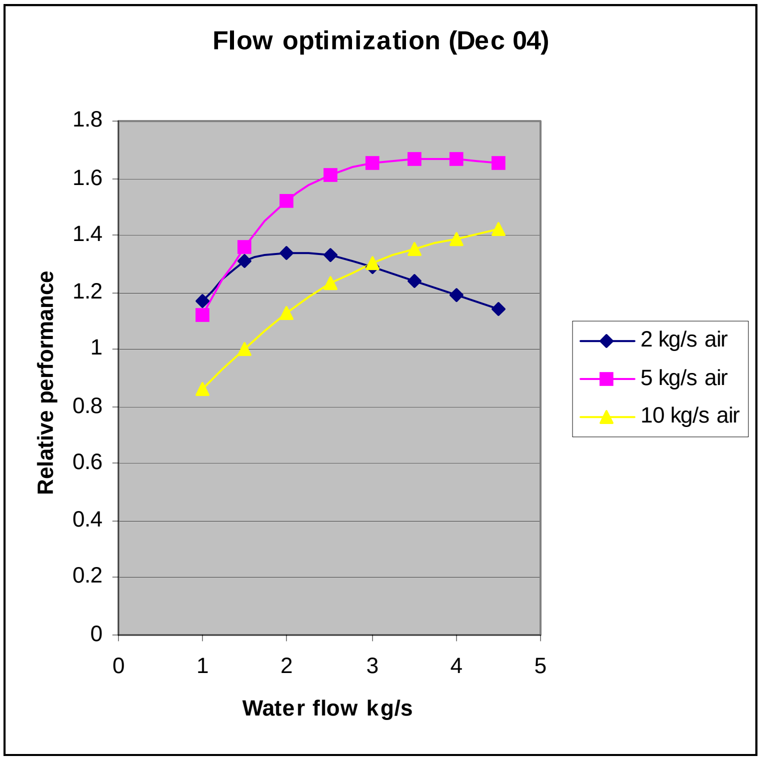

Figure 4. Optimization of Air and Water Flows in SQU Al-Hail Seawater Greenhouse.

Table 3. Options for Improving Water Output.

Options	Optimal Flows		Relative
	Air*	Water $L.s^{-1}$	Freshwater Output
Add 50% more solar collector	38%	1.6 + 1.4†	2.00
Optimise air and water flows	41%	3.5	1.67
Optimise air flow only	31%	1.6	1.49

*relative to current arrangement
†flows through internal and external collectors respectively
values based on analysis of December conditions

4. Closing Remarks

The water output data from the modeling are quite high, due to the assumption that a deepsea pipeline was being used to bring cold seawater to the condensers. This is an interesting concept for the Caribbean and Latin American region where there are several sites where this approach could be used. However, a distinction needs to be made between this approach and the one used at the Al-Hail greenhouse which does not use such a pipeline. This site employs outlet water from the evaporators as cooling water for the condensers. This water is not as cold as deep seawater and therefore overall freshwater production is less.

The aim of constructing the Seawater Greenhouse in Oman was to demonstrate the technology to local farmers and companies in the Arabian Gulf. There are several benefits for the development of the humidification-dehumidification Seawater Greenhouse system in arid regions. It provides for additional water supplies for other purposes such as the development of environmental projects. It also allows for the reclamation of salt-affected land by not relying, at all, on groundwater resources. In addition, it gives the opportunity to develop a high value agricultural sector that is sustainable in the long term and immune to climatic variations. In closing, we believe that this technology will be of real benefit to coastal farmers, worldwide, that are struggling with the problems of salt-affected soil and increasing shortages of groundwater.

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