IDA World Congress on Desalination and Water Reuse, October 2001, Manama, Bahrain

Humidification-Dehumidification Desalination: Seawater Greenhouse Development

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Abstract

The main objective of our study was to determine 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. A thermodynamic model was used based on heat and mass balances. The thermodynamic and economic efficiencies of solar water desalination systems were also briefly reviewed. While humidification-dehumidification solar distillation plants have been around for over a century, the concept of using them in combination with the growth of crops in a greenhouse system is relatively new. With the system under study in our laboratory (i.e. Seawater Greenhouse), surface seawater trickles down a porous front wall evaporator through which air is drawn into the greenhouse. The saturated air passes through a condenser, which is cooled using cold deep seawater or cool seawater coming out of the evaporators Thermodynamic modeling (i.e. simulation) of the Seawater Greenhouse system in our laboratory 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. This was greater than a factor of two compared to the worst-case scenario with the same overall area (50 m wide by 200 m deep), which gave 58 $m^3.d^{-1}$. Low power consumption went hand-in-hand with high efficiency. The wide shallow greenhouse consumed 1.16 kW. m^{-3}, while the narrow deep structure consumed 5.02 kW. m^{-3}. Total fresh water production for three climate scenarios was also calculated. The benefits of the development of the Seawater Greenhouse in arid regions such as the Arabian Gulf were discussed.

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Introduction

There is a growing realization in arid and non-arid countries that the long-term solution to a shortage of potable water lies in a coordinated approach involving water management, purification, and conservation (Goosen and Shayya, 1999). A key feature to this approach is the development of environmental friendly water purification techniques. While the most common desalination methods are based on thermal and membrane principles, alternative techniques, such as solar desalination, are also being considered. Solar methods are well-suited for the arid and sunny regions of the world as in the Arabian peninsula (Goosen et al., 2000; Hamed et al., 1993; Kumar and Tiwari, 1998).

A variety of solar desalination devices have been developed. One of the more successful examples is the multiple-effect still (Figure 1). Latent heat of condensation is recovered so as to increase production of distillate water and improve system efficiency. It may be carried out in two or more stages, generally referred to as multi-effect solar distillation. 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).

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) noted that there is a shortage of research on economic analysis to determine the ultimate cost of the water product. Materials of construction, plant size and location, and operating costs (i.e., energy and labor) must all be taken into account. Therefore, both efficiency and economics need to be considered when choosing a solar desalination system.

The main objective of our study was to determine 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. A thermodynamic model was used based on heat and mass balances. The thermodynamic and economic efficiencies of solar water desalination systems were also briefly reviewed.

Efficiency of Multiple-Effect Solar Stills

Good overviews of solar desalination schemes are given by Goosen et al (2000) and Hamed et al. (1993). A multiple-effect distiller is generally more effective thermodynamically than a single-effect distiller since the former uses the available heat energy more than once. Single and double-basin solar stills can also be coupled with a flat-plate collector to enhance the distillate output. In a study by Yadav and Jha (1989), a transient analysis was presented of a double-basin solar still coupled with a flat-plate solar collector. A paper by Kumar et al. (1989) was devoted to the development of a transient model to study the performance of a double-basin solar still. The still was integrated with a heat exchanger in order to enhance its distillate output per unit area. This integration was achieved by flowing hot fluid through the still. The use of waste hot water (available from power or chemical plants), for example, is of great importance since it can significantly enhance the daily distillate output of a still.

Multiple-effect solar desalination systems are more productive or efficient than single basin stills in producing fresh water due to the reuse of latent heat of condensation. The increase in efficiency must be compared to (i.e., balanced against) the increase in capital and operating costs of a multi-effect solar still compared to a simpler single-basin solar still. The efficiency of a multiple-effect solar still can be increased, for example, by inclining the glass cover surface towards the sun and installing weirs (i.e., groves) on the upper surface of the glass to hold and warm the saline water before it enters the still. The efficiency of the system can also be improved by running it in an upward-type mode with the saline water evaporating from the upper surface of a glass plate and then having the vapor condense on the lower side of the glass plate immediately above the first plate. At low solar radiation, employing flowing air to carry away most of the vapor between the plates will improve the total solar radiation reaching the saline water. The efficiency of the system may further be improved by employing mathematical modeling to optimize still efficiency. The addition of flat plate collectors and heat exchangers to transfer waste heat from local industry/plants to the solar still provides an additional way of enhancing the productivity of the system.

Economics of Solar Desalination

A review of cost-estimation of solar desalination systems was reported by Delyannis and Belessiotis (1999). They noted that solar energy conversion plants are capital-intensive enterprises. According to the authors, a general economic analysis is not easy to accomplish since only few studies report on predicting the price of water or focus on economics. For solar distillation plants, the problem is compounded with the fact that most of them are constructed from inexpensive local materials using local personnel. In such a situation, prices differ considerably from one location to another. Hoffman (1992) presented a detailed theoretical cost analysis based on real operational data for solar driven desalination plants. He concluded that the price of water from solar-powered desalination plants ranges from 0.52 to 1.59 $\$.m^{-3}$. The figures apply to capacities over 100,000 $m^3\ d^{-1}$.

In a related area, Voivontas et al. (1999) analyzed water management strategies based on advanced desalination schemes (such as reverse osmosis and electrodialysis) powered by renewable energy sources (such as wind and solar energy). A framework was presented for developing a decision procedure that monitors water shortage problems and identifies the availability of renewable energy resources to power desalination plants. The cost of alternative solutions, taking into account energy costs or profits by energy selling to a grid, was estimated. Emphasis was given to the market forces and the relationships among technology prices and market potential. While their study is based on the application of wind and solar energy to run a RO desalination plant rather than direct solar distillation, it does give a good description of the factors and decision steps that need to be taken into account (e.g., inflation rate and investment life) when estimating water production costs.

Humidification-Dehumidification Systems

The earliest humidification-dehumidification solar distillation plant on record was designed and built in 1872 by Charles Wilson in Chile (Talbert et al., 1970). The still produced 22.7 $m^3.d^{-1}$ (6000 US gallons per day - gdp) of fresh water for a mining operation. The still was still in operation 36 years later. The concept of humidification of air, followed by dehumidification to collect fresh water is, therefore, not new. It was further developed at the University of Arizona in 1961 in cooperation with the Georgia Institute of Technology and the University of Sonora, Mexico at Puerto Peñasco, New Mexico. The group built a pilot plant called "humidification cycle distillation". Specifically, solar energy was employed to preheat the saline water for the humidification-dehumidification cycle.

A more recent example of a humidification-dehumidification system is a pilot plant built at Kuwait University (Delyannis and Belessiotis, 1999). The system consisted of a salt gradient solar pond, 1,700 m^2 in surface area, used to load the air with humidity. Fresh water was collected by cooling the air in a dehumidifying column, producing 9.8 $m^3 \cdot d^{-1}$ distillate. An air-dehumidification method suitable for coastal regions was also described by Khalid (1993). Khalid noted that the method was economic if the fresh water was considered as an air conditioning by-product.

Paton and Davis (1996) used the humidification-dehumidification method in a greenhouse-type structure for desalination and for crop growth (Figure 2). 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 surface heated by the sun and cold water drawn from below the sea surface was the driving force in the system. The greenhouse acted as a solar still providing a controlled environment inside the greenhouse. A thermodynamic model was employed in the greenhouse.

In a similar study, a closed air cycle humidification-dehumidification process was used by Al-Hallaj et al. (1998) for water desalination. The circulated air by natural or forced convection was heated and humidified by the hot water obtained either from a flat plate solar collector or from an electrical heater. The latent heat of condensation was recovered in the condenser to preheat the saline feed water (Figure 3

While the concept of humidification of air, followed by dehumidification to collect fresh water dates back more than 100 years, the idea of using a humidification-dehumidification system for the growth of crops in a controlled environment of a greenhouse is relatively new. Mathematical models (i.e., thermodynamic models) need to be employed to optimize the desalination system performance. Several humidification-dehumidification pilot plants have been built around the world. Lower operating costs in the form of alternative energy sources (e.g. waste heat or wind energy) were found to be key factors in their economic viability.

Methodology

Thermodynamic Simulation Model: A software program developed by Light Works Limited, England was used to model thermodynamic analysis of the humidification/dehumidification Seawater Greenhouse system. The computer program consisted of several modules: Seapipe, Airflow, Evaporator 1, Roof, Planting Area, Evaporator 2, Condenser (air/water heat exchanger)

Input Data for Model: The software needs a weather data file and a bathymetric (seawater temperature) file. These are specific to a location. In the present analysis weather data for the year 1995 obtained from the Meteorological Office situated at Seeb Airport were used. 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 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, condenser); Seawater pipe; Air exchange.

Simulation runs: In the present analysis three parameters i.e. dimension of the greenhouse, rooftransparency and height of the front evaporator were taken as variables. These parameters were varied as follows: Dimensions of Greenhouse (width x length): Area was kept constant = 10^4 m^2; 50 x 200, 80 x 125, 100 x 100, 125 x 80 and 200m x 50m; Transparency of Roof 0.63 x 0.63 and 0.77 x 0.77; Height of the Front Evaporator 3 and 4m . The parameters kept constant were: Height of Planting Area = 4m; Height of the Rear Evaporator = 2m; Height of the Condenser = 2m, Orientation of Greenhouse = 40^o N; Seawater pipe diameter = 0.9m, length = 5000m; Volumetric flow = 0.1m^3/s; Pit depth = -3m, height = 7.5m, wall thickness = 0.1m; Air change = 0.15 (fraction)/min; Fin spacing = 0.0025m and depth = 0.1506m

Results and Discussion

Thermodynamic modeling (i.e. simulation) of the Seawater Greenhouse system in our laboratory has shown that the dimension of the greenhouse (i.e. width to length ratio) had the greatest overall effect on water production and energy consumption, Figures 4 and 5, 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 4.5 to 1.4 kW. 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 thirty simulation runs were carried out with one year weather data. The water production and power consumption data were analyzed using Statistical Analysis System (SAS) program. Analysis of variance (ANOVA) procedure was used to detect the significance of dimension of *Greenhouse*, transparency of roof materials and height of the front evaporator.

The overall effects of roof transparency and evaporator height on water production were not significant, Figures 5 and 6, respectively. However, 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 (Table 1). This was greater than a factor of two compared to the worst-case scenario with the same overall area (50 m wide by 200 m deep) and same evaporator height, which gave 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. m^{-3}, while the narrow deep structure consumed 5.02 kW. m^{-3} .

While these results suggest that a wide shallow greenhouse is technically 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. The condenser may end up being the bottleneck in the overall economic viability of this greenhouse humidification-dehumidification system.

Total fresh water production for three climate scenarios was also calculated. The water production rate results from the simulations using optimized and constant values for fan and pump speeds were as follows: temperate, 20370 m^3 .y^{-1} hectare^{-1}; tropical, 11574 m^3 .y^{-1} .hectare^{-1}; and oasis 23529 m^3 .y^{-1} .hectare^{-1}.

Concluding Remarks

To be able to produce commercially viable solar desalination systems, both efficiency and economic criteria need to be satisfied. Optimum water production must be balanced against any increase in the capital and operating costs of the plant. The final cost of the water produced must, at worst, not be higher than the cost of fresh water produced by conventional means such as multistage flash or multiple-effect evaporators. In the case of humidification-dehumidification systems, the energy costs associated with the condensers and pump operation as well as the energy saving associated with coupling the system to waste heat energy sources may end up being crucial in developing a commercially viable system. All of this in turn is dependent on a thorough understanding of the thermodynamic efficiency, as well as the economics of building a plant at a specific location.

Finally, there are several benefits for the development of the humidification-dehumidification Seawater Greenhouse system in arid regions such as the Arabian Gulf. It allows for the opportunity to develop a high value agricultural sector that is sustainable in the long term and immune to climatic variations. It gives new market options for import substitution and export development. It provides for additional water supplies for other purposes and it allows for the development of environmental projects.

Acknowledgments

This study has been made possible through funding from the Middle East Desalination Research Center (MEDRC) through contract number 97-A-005b.

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Table 1. Results of the simulation runs for Oman using Waterworks' software and one year of data

Run #	Greenhouse Dimensions		Evaporator Height (m)	Roof Transparency (%)	Water Production (m^3/day)	Power Consumption (kW/m^3)
	Width (m)	Length (m)				
1	50	200	2	0.4	57.8	5.02
2	80	125	2	0.4	73.4	2.46
3	100	100	2	0.4	79.5	2.02
4	125	80	2	0.4	83.8	1.75
5	200	50	2	0.4	125.5	1.16
6	50	200	2	0.6	62.7	4.52
7	80	125	2	0.6	78.1	2.34
8	100	100	2	0.6	85.5	1.86
9	125	80	2	0.6	90.7	1.61
10	200	50	2	0.6	98.9	1.34
11	50	200	3	0.4	58.9	4.48
12	80	125	3	0.4	74.0	2.37
13	100	100	3	0.4	74.0	2.37
14	125	80	3	0.4	84.9	1.69
15	200	50	3	0.4	91.8	1.43
16	50	200	3	0.6	63.0	4.21
17	80	125	3	0.6	79.5	2.17
18	100	100	3	0.6	79.5	2.21
19	125	80	3	0.6	91.0	1.57
20	200	50	3	0.6	98.6	1.34
21	50	200	4	0.4	58.6	4.38
22	80	125	4	0.4	74.0	2.30
23	100	100	4	0.4	79.5	1.93
24	125	80	4	0.4	84.9	1.68
25	200	50	4	0.4	93.2	1.41
26	50	200	4	0.6	93.2	1.41
27	80	125	4	0.6	79.5	2.16
28	100	100	4	0.6	85.2	1.79
29	125	80	4	0.6	90.4	1.58
30	200	50	4	0.6	97.5	1.35

Figure Legends

1. Typical multi-effect multi-wick solar still (adapted from Fath, 1998).

2. Seawater Greenhouse (Goosen et al, 2000): 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 sea water 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.

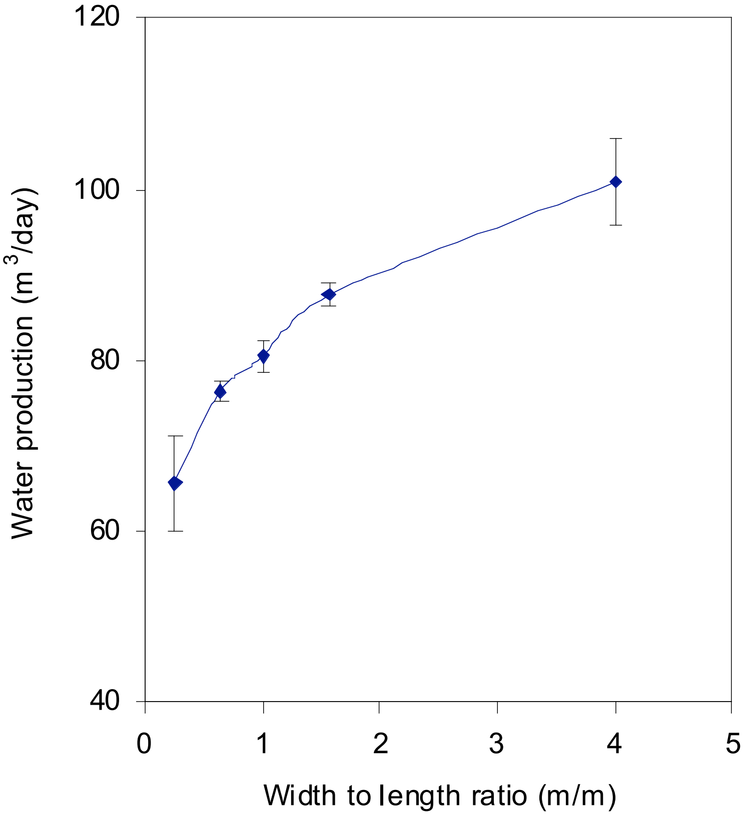
3. Schematic of a closed-air and open-water humidification-dehumidification unit (adapted from Al-Hallaj et al., 1998).

4. Overall effect of width to length ratio on water production rate.

5. Overall effect of width to length ratio on energy consumption.

6. Overall effect of evaporator height on water production.

7. Overall effect of roof transparency on water production.


120
100
80
60
40
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1
2
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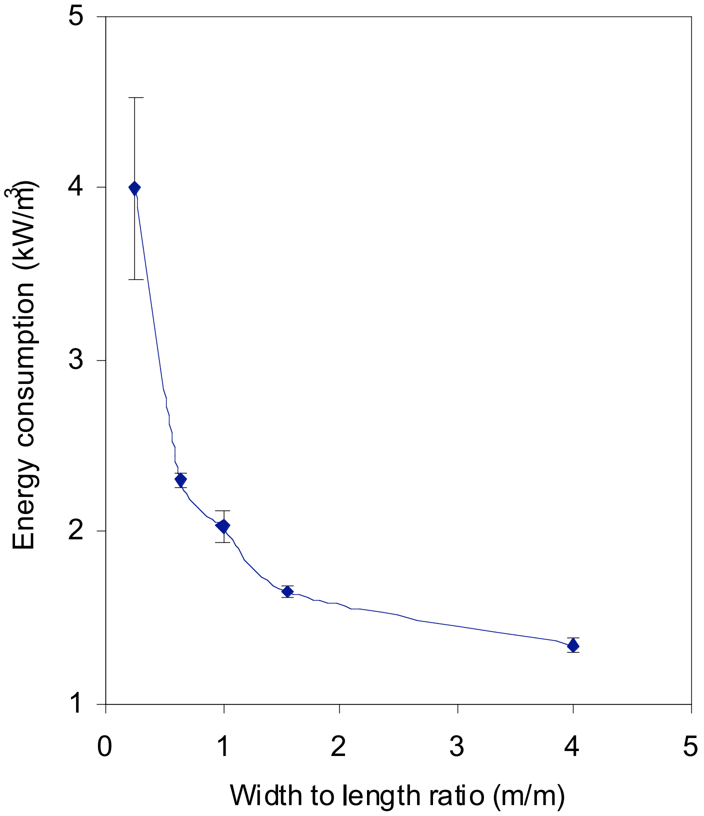
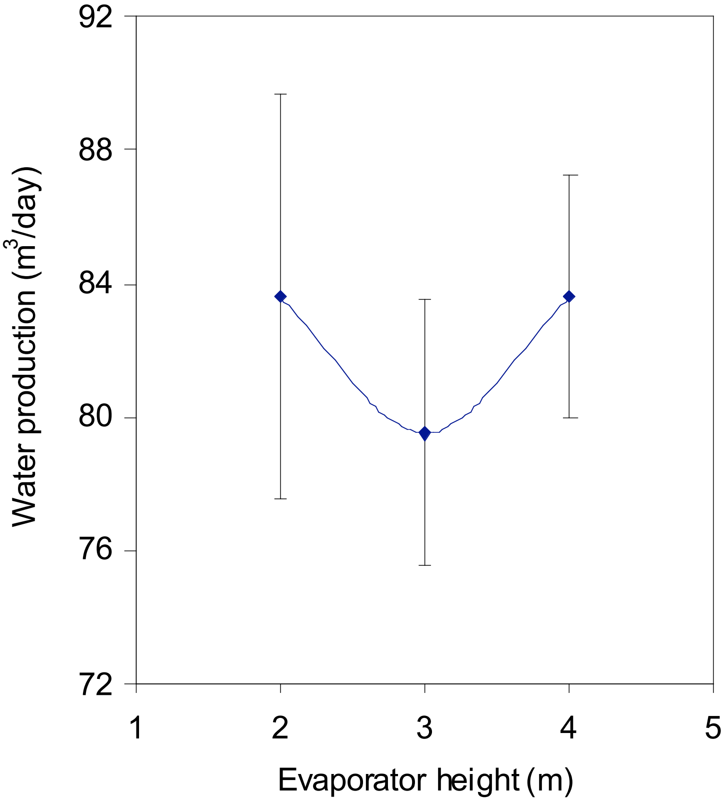
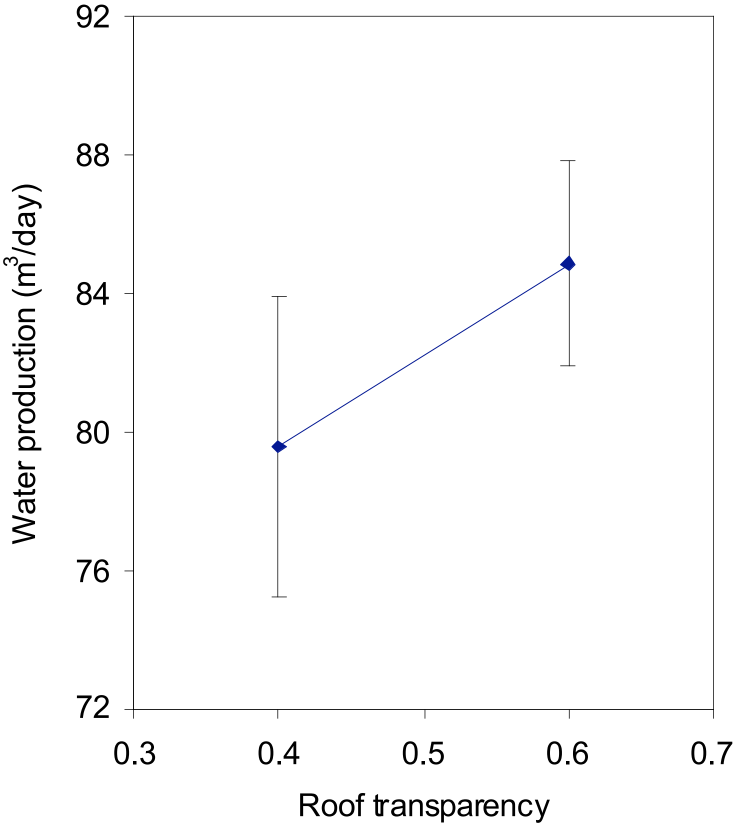
4
5
Water production (m^3/day)
Width to length ratio (m/m)


Energy consumption (kW/m^3)
Width to length ratio (m/m)
1
2
3
4
5
0
1
2
3
4
5


92
88
84
80
76
72
1
2
3
4
5
Water production (m3/day)
Evaporator height (m)


92
88
84
80
76
72
0.3
0.4
0.5
0.6
0.7
Roof transparency
Water production (m3/day)