WATER DESALINATION BY HUMIDIFICATION AND DEHUMIDIFICATION OF AIR, SEAWATER GREENHOUSE PROCESS

Karim Bourouni, Mohamed Thameur Chaibi and Ali Al Taee
UR EBSS Ecole Nationale d’Ingénieurs de Tunis, BP 37, 1002 Le Belvédère, Tunisie INGREF

Keywords: Water Desalination, Humidification, Dehumidification, Seawater greenhouse

Contents

1. Introduction
2. Desalination Process by Humidification and Dehumidification
   2.1. Moist Air
   2.2. Humidifying with Cooling and Dehumidifying Processes
   2.3. Using Humidification Dehumidification (HD) Process in Desalination
   2.4. Heat and Mass Transfer in HD Desalination Process
   2.5. Overview on Some Desalination HD Projects
   3.1. Process Description
   3.2. The Condenser in the SWGH
   3.2.1. Different Condenser Layouts in SWGH
   3.2.2. Cooling the Condenser
   3.3. The Evaporator (Humidifier) in the SWGH
   3.4. The planting area in the SWGH
   3.5. Construction and Materials
   3.6. Energy Requirements
   3.7. Economics and Applications
4. Design of SWGH
   4.1. Simplified Model of Heat and Mass Transfer inside the SWGH
   4.2. Efficiency of the Evaporative cooling
   4.3. Design of Condensers
   4.4. Venting System
   4.5. Detailed Thermodynamic Model for SWGH
5. Overview on the installed SWGH projects: Case Studies
   5.1. Case Study 1: The SWGH project in Tenerife
       5.1.1. Description of the Pilot Plant
       5.1.2. Performances of the SWGH
   5.2. Case Study 2: The SWGH Project in UAE
       5.2.1. Description of the Pilot Plant
       5.2.2. Performances of the Pilot Plant
   5.3. The SWGH Project in Oman
       5.3.1. Description of the Pilot Plant
       5.3.2. Performances of the SWGH
6. Conclusion
Glossary
Bibliography
Biographical Sketches

Summary

The Seawater Greenhouse (SWGH) is a novel concept which combines natural processes and simple construction techniques to provide a low-cost solution to one of the world's greatest needs - fresh water. SWGH is a new development that offers sustainable solution to the problem of providing water for agriculture in arid coastal regions. The process uses seawater to cool and humidify the air that ventilates the greenhouse and sunlight to distil fresh water from seawater. Fresh water is condensed out of the humid air. This enables the year round cultivation of high value crops that would otherwise be difficult or impossible to grow in hot and arid regions.

In this work an overview on the fundamentals and applications of SWGH is presented. It includes basic process design, system configuration, choice of material and components.

The process is analyzed from thermodynamic point of view; heat and mass transfer occurring in the different components of seawater greenhouses are detailed. The corresponding models are discussed and analyzed. A particular interest was given to the cooling process of the condenser used in SWGH since it is the major limiting concept.

The performance of the process in different locations and the influence of the climate conditions (radiation, humidity and wind velocity) are investigated. Finally, a number of pilot plants installed worldwide in Canary Islands, UAE and Oman are presented and their performances discussed.

1. Introduction

The continued growth of demand for water and increasing shortage of supplies are two of the most certain and predictable scenarios of the 21st century. Population growth is threatening the availability of fresh water in many regions of the world.

Over a billion people do not have access to a safe supply of water and the number is growing. Large areas of the world already suffer from drought while deserts and populations increase in size. Rainfall remains broadly constant, yet demand for water has doubled in the last 20 years. As demand outstrips renewable supply, the depletion of ground water is accelerated. In coastal regions this causes saline intrusion which reduces the ability to grow crops and is now a major problem in many parts of the world (Vorosmarty et al. 2000).

Agriculture accounts for 70% of fresh water used globally. This percentage is often higher in regions that suffer from chronic water shortages. In the Middle East and North Africa, for example, up to 90% of available water is used in agriculture (Mahmoudi et al. 2010a).
Agriculture, with a high demand for water, will be a major pressure point. Conventional agriculture is very inefficient in its use of water. Of all the water used to irrigate crop, less than 1% can be expected to find its way into the final edible product. As fresh water resources are finite, there is an inexorable pressure to reduce agricultural use of water (Goosen and Shayya 1999; Paton ans Davies 1996; Mahmoudi et al. 2008; Mahmoudi et al. 2009a; Mahmoudi et al. 2010a; Mahmoudi et al. 2009b; Khalil 1993).

Although seawater is abundant, conventional desalination consumes substantial energy, usually derived from fossil fuels. There is a need for affordable and sustainable means of producing food and water, without reliance on energy reserves. Meanwhile, there is a growing opinion that future solutions should involve not only cheaper and better ways of providing freshwater, but also more economical ways of using this increasingly precious resource.

The humidification–dehumidification process (HD) is a versatile technique that can be adapted for water desalination (Mahmoudi et al. 2010a). This method has several advantages such as flexibility in capacity, moderate installation and operating costs, simplicity, possibility of using low temperature and the use of renewable energy (e.g. solar, geothermal, recovered energy or cogeneration). One of the most promising HD processes we can mention here is the Seawater Greenhouse (SWGH).

The SWGH, employing humidification–dehumidification processes, provides a possible solution to this dilemma by creating a growing environment that substantially reduces the amount of water required for irrigation, in addition to providing a new source of fresh water (Trieb et al. 2000, Hamed et al. 1993, Kumar and Tiwari 1998, Al Hallaj et al. 1998 and Fath 1998). It is a method of cultivation that provides desalination, cooling and humidification in an integrated system. Its purpose is to provide a sustainable means of agriculture in arid coastal areas where the scarcity of freshwater and expense of desalination threaten the viability of agriculture.

There are several benefits for the development of the SWGH 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-infected 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.

Even in efficient irrigation systems, a very large fraction of the water is lost through transpiration.

Plant scientists have studied mechanisms of water loss in great details. The classic model for representing water loss from crops is the Penman equation which compares the process to evaporation from an open pool of water (Allen et al. 1998). In simple terms the equation can be written as:

$$\text{Rate of water loss} = b R + c D$$  \hspace{0.5cm} (1)

Where $R$ is the net radiation received by the crop. The term $D$ is the vapor deficit, meaning the difference between the saturation vapor content of the air and its actual vapor content.
The terms \( b \) and \( c \) are approximately constant for a given range of conditions.

The Penman equation suggests two strategies for reducing water requirements.

i. Reduction of the radiation \( R \) by means of shading; or possibly selective shading to favor photosynthetically active wavelengths of light.

ii. Reduction of the vapor deficit \( D \) through humidification of the air.

Both of these strategies are employed in the SWGH. In addition, the Greenhouse addresses the issue of excessive water loss from crops by incorporating them in a system that recovers some of the transpired water. The SWGH combines, in a single system, desalination with a water-efficient method of cultivation.

Although the common methods of desalination such as distillation and reverse osmosis have been the subject of many investigations, studies of the HD process and in particular SWGH have been limited. A rigorous mathematical model describing the basic phenomena (heat and mass transfer) occurring in the different components of greenhouse (evaporators, condensers and cultivating areas) is required to design and evaluate the performances of new and existing systems.

Moreover, the efficiency of SWGH depends on the climate conditions. Because the desalination process is driven mainly by solar energy, sunlight is the weather variable that most influences the performance of the SWGH. However, other variables such as wind and humidity are also significant and this means that the optimum design and mode of operation may vary across the regions. Hence, the mathematical modeling of the process must take into account all these phenomena.

After the initiation in 1991 and the installation of several prototypes worldwide (Canary Islands, UAE and Oman), today, SWGH is ready for implementation in any arid region where a sustainable approach to agriculture and water production is needed.

2. Desalination Process by Humidification and Dehumidification

The SWGH is a desalination process using air humidification and dehumidification (HD). Like all the HD desalination processes, the moist air is used as a mean transporting the vapor from the humidifier (evaporator) to the dehumidifier (condenser).

All engineering calculations required to design and model SWGH system start with estimations of the air-water vapor mixture properties that are the basis for heat and mass balances. It is widely used to illustrate and analyze the change in properties and the thermal characteristics of the air -HD process and cycle.

2.1. Moist Air

For thermal analysis, moist air may be treated as a binary mixture of dry air and water vapor. The composition of dry air varies slightly at different geographic locations and from time to time. The variation of water vapor has a critical influence on the characteristics of moist air. The moist air can be considered as ideal gas; hence the
relationship between its thermodynamic properties can be given by the following equation of state:

\[ p_v = R T \]

where

\[ p = \text{pressure of the gas}, \]
\[ v = \text{specific volume of the gas}, \]
\[ R = \text{gas constant}, \]
\[ T = \text{absolute temperature of the gas}, \]

The most exact calculation of the thermodynamic properties of moist air is based on the formulations recommended by Hyland and Wexler (1983) of the U.S. National Bureau of Standards. The psychrometric charts and tables developed by ASHRAE are calculated and plotted from these formulations (Wang and Lavan 1999). Applying Dalton’s law to moist air gives:

\[ P_{at} = p_a + p_w \]

where:

\[ P_{at} = \text{atmospheric pressure of the moist air}, \]
\[ p_a = \text{partial pressure of dry air}, \]
\[ p_w = \text{partial pressure of water vapor}, \]

The moist air state can be described by several parameters:

i. **Humidity and Enthalpy**

The *humidity ratio* of moist air, \( w \), in (kg H\(_2\)O/kg dry air) is defined as the ratio of the mass of the water vapor, \( m_w \), to the mass of dry air, \( m_{da} \) (Wang and Lavan 1999):

\[ w = \frac{m_w}{m_{da}} = 0.61298 \frac{p_w}{p_{at} - p_w} \]

The *relative humidity* of moist air, \( \phi \), or RH, is defined as the ratio of the mole fraction of water vapor, \( x_w \), to the mole fraction of saturated moist air at the same temperature and pressure, \( x_{ws} \). Using the ideal gas equations, this relationship can be expressed as:

\[ \phi = x_w / x_{ws} \bigg|_{T,P} = p_w / p_{ws} \bigg|_{T,P} \]

and
\[ x_w = \frac{n_w}{n_{da} + n_w}; \quad x_{ws} = \frac{n_{ws}}{n_{da} + n_{ws}} \]

\[ x_{da} + x_w = 1 \quad (6) \]

Where

- \( p_{ws} \) = pressure of saturated water vapor,
- \( T \) = temperature,
- \( n_{da}, n_w, n_{ws} \) = number of moles of dry air, water vapor, and saturated water vapor,

Then, within the temperature range 0 to 100°C, the enthalpy of the moist air can be calculated as:

\[ h(T, w) = c_{p, da} T + w (h_{g0} + c_{p, w} T) \quad (7) \]

where

- \( c_{p, da}, c_{p, w} \) = specific heat of dry air and water vapor at constant pressure,
- \( h_{g0} \) = specific enthalpy of saturated water vapor at 0°C.

### ii. Moist Volume, Density, Specific Heat, and Dew Point

The specific moist volume \( v \), is defined as the volume of the mixture of dry air and the associated water vapor when the mass of the dry air is exactly 1 kg:

\[ v = \frac{V}{m_a} \quad (8) \]

where \( V \) = total volume of the moist air. Since moist air, dry air, and water vapor occupy the same volume,

\[ v = \frac{RT_R}{P_a (1+1.6078w)} \quad (9) \]

**Moist air density**, often called air density \( \rho \), is defined as the ratio of the mass of dry air to the total volume of the mixture, or the reciprocal of the moist volume:

\[ \rho = \frac{m_a}{V} = \frac{1}{v} \quad (10) \]

The **sensible heat of moist air** is the thermal energy associated with the change of air temperature between two state points. In Equation (7), \( (c_{p, da} + wc_{p, w})T \) indicates the
sensible heat of moist air, which depends on its temperature $T$. 

**Latent heat of moist air**, often represented by $w \cdot h_w$, is the thermal energy associated with the change of state of water vapor.

$$c_{p,a} = c_{p,du} + wc_{p,w} \quad (11)$$

The *dew point temperature* $T_{dew}$, is the temperature of saturated moist air of the moist air sample having the same humidity ratio at the same atmospheric pressure. Two moist air samples of similar dew points $T_{dew}$ at the same atmospheric pressure have the same humidity ratio $w$ and the same partial pressure of water vapor $p_w$.

### iii. Wet Bulb Temperature

The *wet bulb temperature* of moist air $T_{wb}$, corresponds to the equilibrium temperature of water mass evaporating in air in the case where the heat required for evaporation is extracted from air. The difference $(T - T_{wb})$ is representative of the relative humidity HR of air since:

- It is equal to zero if air is saturated (HR=100%): no evaporation is possible
- It increases with the difference $(p_w(T) - p_w)$, which is the motor term of mass transfer, hence it decreases when $HR = p_w / p_w(T)$ increases.

### iv. Psychrometric Charts

Moist air has seven independent thermodynamic properties or property groups: $h$, $T$, $\varphi$, $T_{wb}$, $p_{at}$, $\rho - V$ and $w - p_w - T_{dew}$. When $p_{at}$ is given, any additional two of independent properties determine the state of moist air on the psychrometric chart and the remaining properties.

A *psychrometric chart* is a graphical presentation of the thermodynamic properties of moist air and various air-conditioning processes and air-conditioning cycles (eg: the case of HD process). A psychrometric chart also helps in calculating and analyzing the work and energy transfer. Psychrometric charts currently use two kinds of basic coordinates (Wang and Lavan 1999):

1. **$h$-$w$ charts**: In $h$-$w$ charts, enthalpy $h$, representing energy, and humidity ratio $w$, representing mass, are the basic coordinates. Psychrometric charts published by ASHRAE and the Charted Institution of Building Services Engineering (CIBSE) are $h$-$w$ charts.

2. **$T$-$w$ charts**: In $T$-$w$ charts, temperature $T$ and humidity ratio $w$ are basic coordinates. Psychrometric charts published by Carrier Corporation, the Trane Company, etc. are $T$-$w$ charts (Wang and Lavan 1999).
Figure 1 shows an abridged ASHRAE psychrometric chart.

![Abridged ASHRAE Psychrometric Chart](image)

Figure 1. The abridged ASHRAE psychrometric chart: (i) the determination of moist air properties (ii) air properties change in HD process

### 2.2. Humidifying with Cooling and Dehumidifying Processes

In a *humidifying process*, water vapor is added to moist air and increases the humidity ratio of the moist air entering the humidifier if the moist air is not saturated. In HD process, humidification of moist air is usually performed by evaporation from a water spray, or a wetted medium. The humidifying capacity is given by:

$$m_{ha} = \dot{V}_s \rho_s (w_{out} - w_{in})$$  \hspace{1cm} (12)

where \(w_{out}, w_{in}\) = humidity ratio of moist air leaving and entering the humidifier.

Generally, nozzles are used to spray preheated water into moist air in order to humidify it. A condenser (generally cooling coil) is used to cool and dehumidify the moist air. When moist air flows through the humidifier, the moist air is humidified and approaches saturation. This actual adiabatic saturation process approximately follows the thermodynamic wet bulb line on the psychrometric chart as shown by line a–b (Figure 1). The humidity ratio of the moist air is increased while its temperature is reduced. The cooling effect of this adiabatic saturation process is called *evaporative*...
cooling.

In a cooling and dehumidifying process, both the humidity ratio and temperature of moist air decrease. Some water vapor is condensed in the form of liquid water, called a condensate. This process is shown by curve b-c on the psychrometric chart in Figure 1. Three types of heat exchangers are used in a cooling and dehumidifying process: (1) water cooling coil; (2) direct expansion DX coil, where refrigerant evaporates directly inside the coil’s tubes; and (3) air washer, in which chilled water spraying contacts condition air directly (Wang and Lavan 1999). The temperature of chilled water entering the cooling coil or air washer \( T_{\text{we}} \), determines whether it is a sensible cooling or a cooling and dehumidifying process. If \( T_{\text{we}} \) is smaller than the dew point of the entering air in the washer, or \( T_{\text{we}} \) makes the outer surface of the water cooling coil \( T_{\text{sot}} < T_{\text{dewin}} \) it is a cooling and dehumidifying process. If \( T_{\text{we}} \geq T_{\text{dewin}} \) sensible cooling occurs. The cooling coil’s load or the cooling capacity of the air washer \( q_{\text{cc}} \), is:

\[
q_{\text{cc}} = \dot{m}_{\text{s}} \left( h_{a,\text{in}} - h_{a,\text{out}} \right) - \dot{m}_{\text{c}} h_{\text{c}}
\]

where

\[
h_{a,\text{in}}, h_{a,\text{out}} = \text{enthalpy of moist air entering and leaving the coil or washer,}
\]

\[
\dot{m}_{\text{c}} = \text{mass flow rate of the condensate,}
\]

\[
h_{\text{c}} = \text{enthalpy of the condensate,}
\]

Since the thermal energy of the condensate is small compared with \( q_{\text{cc}} \), in practical calculations the term is often neglected, and

\[
q_{\text{cc}} = \dot{m}_{a} \left( h_{a,\text{in}} - h_{a,\text{out}} \right)
\]

The sensible heat ratio of the cooling and dehumidifying process \( \text{SHR}_{\text{c}} \) can be calculated from

\[
\text{SHR}_{\text{c}} = \frac{q_{\text{cs}}}{q_{\text{cc}}}
\]

where \( q_{\text{cs}} \) = sensible heat removed during the cooling and dehumidifying process.

\( \text{SHR}_{\text{c}} \) is shown by the slope of the straight line joining points b and c. The relative humidity of moist air leaving the water cooling coil or DX coil depends mainly on the outer surface area of the coil including pipe and fins.

2.3. Using Humidification Dehumidification (HD) Process in Desalination

Conventional desalination methods such as MSF, ME, VC and RO are suitable for large
and medium capacity fresh water production (100-50,000 m³/day). El Dessouky and Ettouney (2001) presented these processes in detail. These technologies are expensive for small amounts of fresh water and cannot be used in locations where there are limited maintenance facilities (Nafey et al. 2004a-b). On the other hand, most remote arid areas need low capacity desalination systems.

The humidification dehumidification (HD) desalination process is viewed as a promising technique for small capacity production plants. The process has several attractive features, which include conceptual simplicity with respect to other desalination processes, operation at low temperature, ability to utilize sustainable energy sources, i.e. solar and geothermal, and requirements of low technology level (Bourouni et al. 2001, Bouchekima et al. 2001, Houcine et al. 2006, Al-Hallaj et al. 2006). Also, it can be designed to minimize the amount of energy discarded to the surroundings. Capacity of HD units is between conventional methods and solar stills (Nawayesh et al. 1999a-b).

HD units work with distillation under atmospheric conditions by an air loop saturated with water vapor, and has three main sections: the humidifier, dehumidifier and heat source. This can be described by bringing warm unsaturated air into contact with warm saline water under specified conditions in order to reach a certain desired air humidity (Figure 2.a). This step is followed by stripping out the water vapor in the humidified air by passing it through a condenser. The vapor carrying capability of air increases with temperature; 1 kg of dry air can carry 0.5 kg of water vapor and about 2803 kJ when its temperature increases from 30 to 80°C. The HD process should essentially include a heating device for both air and feed water and a humidifying apparatus in order to bring them into contact. In order to achieve a full saturation of the air stream it was found that structured packing in the humidification unit is required (Dai and Zhang 2000). The air/water ratio should be optimized to maximize the system efficiency.

The system design can be based on natural or forced air convection (Bourouni et al. 2001). Air humidification decreases the air density because of the low molecular weight of water. This implies that air will rise in a humidifier because of the decrease in its density. On the other hand, air dehumidification in the condenser would increase the air density. Accordingly, the air would sink in the condenser; hence, a convection cell can be initiated within the system. In the case of forced air convection, a blower is used to move the air from the humidifier to the dehumidifier.

The HD process can be classified also to direct or indirect. In direct HD process the water is in a direct contact with air (e.g. solar still, air washer). The indirect solar HD process has the advantage of separating the heating surface from the evaporation zone, and therefore, the heating surface is relatively protected from corrosion or scale deposits. The HD process can be used in a closed or open air cycle. In an open air cycle, the amount of fresh air feed to the unit increases water productivity while the closed air cycle has the higher thermal efficiency.

Several layouts for the humidification dehumidification process can be considered (Ettouney 2005) including the conventional system combined with either one of the following units to condense/extract the water vapor from the air: (1) water condenser,
(2) membrane air drying, (3) vapor compressor, and (4) lithium bromide absorption desorption (Figure 2).

Figure 2. Different layouts of Humidification Dehumidification (HD) process (a) Conventional Humidification Dehumidification process; (b) Humidification vapor compression; (c) Humidification process combined with desiccant material; (d) Humidification and membrane drying, (Ettouney, 2005)

Figure 3 shows a typical closed loop HD process configuration driven by solar energy (Nafey et al. 2004a); the corresponding thermodynamic cycle is presented in the Figure 1. In this process solar collectors are used to preheat water and air.

The disadvantage of the HD is the low conversion ratio in the humidifier which is less than 0.01 kg product per 1 kg water flowing in the humidifier (Muller-Holst et al. 1999). This ratio is increased upon the increase of the hot water temperature, air and water flowrates. On the other hand, the evaporation efficiency decreases at higher water or air flow rates because of the increase in the sensible heat load of the system. This would reduce the water evaporation rate and humidification efficiency. Reduction of the condenser heat transfer area requires use of finned tube configuration. This is necessary because of the low heat transfer coefficient on the air side; this is irrespective of water vapor condensation, which account for a very small percentage of the entire air stream.
Figure 3. Schematic diagram of (HD) process driven by solar energy, (Nafey et al. 2004a)

TO ACCESS ALL THE 65 PAGES OF THIS CHAPTER, Visit: http://www.eolss.net/Eolss-sampleAllChapter.aspx

Bibliography

Al-Enezi G., Ettouney H., Fawzy N. (2006). Low temperature humidification dehumidification desalination process. Energy Conversion and Management 47, 470–484 [A small capacity experimental Humidification Dehumidification system is studied experimentally to evaluate the process characteristics as a function of the different inlet conditions (temperatures, mass flow, etc.)].


Al-Hallaj S., Farid M.M., Tamimi A.R. (1998). Solar desalination with a humidification-dehumidification cycle: performance of the unit. Desalination 120, 273-280. [This experimental study concerns two different desalination units constructed from different materials and functioning by air humidification and dehumidification. The productivity of the units was compared to single-basin stills].

crop water requirements - FAO Irrigation and drainage paper, 56-94. [This publication presents an updated procedure for calculating reference and crop evapotranspiration from meteorological data and crop coefficients].

Bouchekima B., Gros B., Ouahes R., Dibound M. (2001). Brackish water desalination with heat recovery, Desalination 138, 147–155. [The aim of this research was to develop a highly efficient desalination system of simple construction, applicable in units of less than 1m³/d of fresh water production, suitable also for areas with poor infrastructure].

Bourouni K., Chaibi M., Tadrist L. (2001). Water Desalination by Utilization and Desalination of Air: State of the art, Desalination 137, 167-176. [This paper presents a state of the art related to the Desalination by Utilization of Air. In this paper the SWGH system was tested and the influence of the different parameters on its performances discussed]

Dai Y.J., Zhang H.F. (2000). Experimental investigation of a solar desalination unit with humidification and dehumidification. Desalination 130, 169–175. [A solar desalination unit with Humidification and Dehumidification is presented. Experiments on the unit were conducted and the influence of the different parameters analyzed].

Davies P. (2005). A solar cooling system for greenhouse food production in hot climates, Solar Energy, 79, 661–668. [This paper discussed the efficiency of the evaporative cooling coupled to desiccant desalination system for greenhouses cooling in different climates].

Davies P., Paton C. (2005). The seawater greenhouse in the United Arab Emirates: thermal modeling and evaluation of design options, Desalination 173, 103–11. [The SWGH installed in Abu Dhabi (UAE) is presented. Results are used to calibrate a computational fluid dynamic (CFD) model in order to analyze several design options].

Davies P., Turner K., Paton C. (2004). Potential of the seawater greenhouse in middle eastern climates, International Engineering Conference (IEC) “Mutah 2004”, Mutah University, JORDAN, April 26-28, 523-540. [In this paper the SWGH system is described. The authors made reference to installations in the Canary Islands, the United Arab Emirates and Oman].


Dawoud B., Zurigat Y.H., Kitzinga B., Aldoss T., Theodoridis G. (2006). On the possible techniques to cool the condenser of seawater greenhouses, Desalination 195, 119–140. [In this paper a theoretical study of possible cooling techniques for the condenser of SWGH is presented. Possible candidate techniques are discussed. Theoretical assessment of these techniques is conducted and the results are reported]

El-Dessouky H.T., Ettouney H.M. (2001). Fundamentals of salt water desalination, Elsevier. [The book focuses on the processes widely used in desalination industry (MSF, MED and RO). Also, other desalination processes with attractive features and high potential are considered].

Ettouney H. (2005) Design and analysis of humidification dehumidification desalination process. Desalination 183, 341–352. [This paper evaluates the characteristics of several layouts for the Humidification Dehumidification process].


Farid M.M., Hamad F. (1993). Performance of a single basin solar still, Renewable Energy 3, 75–83. [In this paper a single-basin solar still was tested and the influence of the different parameters on its efficiency was studied].

Fath H.E.S., Ghazy A. (2002). Solar desalination using humidification dehumidification technology. Desalination 142, 119-133. [In this paper a numerical study has been carried out to investigate the performance of a simple solar desalination system using Humidification-Dehumidification processes].

Fath H.E.S. (1998). Solar desalination: A promising alternative for water provision with free energy,
simple technology and a clean environment. Desalination 116, 45-56. [This paper presents an overall review and technical assessment of the various and up-to-date developments in single and multi-effect solar stills].


Goosen M.F.A, Salbani, S.S., Paton C., Perret J., Al-Nuaimi A., Haffar I., Al-Hinai H., Shayya W.H. (2003). Solar energy desalination for arid coastal regions: development of a humification-dehumidification seawater greenhouse, Solar Energy, 75, 413-419 [In this paper one thermodynamic model, based on heat and mass balances, for the SWGH is detailed. This latter was used to determine the influence of greenhouse-related parameters on the process].

Goosen M.F.A, Shayya W. (1999) Water management, purification and conservation in arid climates: vol. I. Water management. Lancaster, PA, USA: Technomic Publishing Co. 1–6. [The aim of this introductory chapter is to provide a brief overview of some of the key water issues facing arid regions. It focuses on different methods for increasing the usable water supply, water pollution and economic development, management of irrigation systems and water policy]


Herbert W. Stanford III. (2003). HVAC Water Chillers and Cooling Towers, Fundamentals, Application and Operation, Marcel Dekker, Inc [This book provides practical information and guidance relative to the application, design, purchase, operation, and maintenance of water chillers and cooling towers.]

Hesselgreaves J.E. (2001). Compact Heat Exchangers, Selection, Design and Operation, Pergamon [The purpose of this book is to summarize industrial concepts that have been developed in the last 10 years in the field of heat exchangers].


Hyland R.W., Wexler A. (1983). Formulations for the Thermodynamic Properties of Dry Air from 173.15 to 473.15 K, and of Saturated Moist Air from 173.15 to 372.15 at Pressures up to 5 Mpa, ASHRAE Trans., 89/2, 520-535. [In this paper, formulations and sample calculations are given for the volume, enthalpy and entropy of dry and moist air, along with relationships for the volume, enthalpy and entropy of saturated moist].

Kassam A., and Smith M. (2001). FAO Methodologies on Crop Water Use and Crop Water Productivity, Paper NO CWP-M07, Expert Meeting on crop water productivity, Rome 3-5 December 2001. [This note provides an overview of the FAO methodologies that have been developed and promoted for the computation of crop water requirements, crop water productivity under adequate and deficit water supply and for irrigation requirements and scheduling.]

Khalil A. (1993). Dehumidification of atmospheric air as a potential source of fresh water in the UAE. Desalination 93, 587–96. [A cooling/dehumidification process to recover water from ambient humid air in coastal regions in UAE was investigated. The process was analyzed and the parameters controlling the heat and mass transfer rates are optimized for the climatic conditions in humid regions in the UAE].

temperature gradients along a greenhouse, a simple climate model was proposed which incorporated the effect of ventilation rate, roof shading and crop transpiration.

Kittas C., Bartzanas T. (2007). Greenhouse microclimate and dehumidification effectiveness under different ventilator configurations. Building and Environment 42, 3774–3784. [In this paper, the efficiency of two different greenhouse ventilation opening configurations on greenhouse microclimate during dehumidification process with simultaneously heating and ventilation was analyzed by means of computational fluid dynamics (CFD) using a commercial program based on the finite volume method.]

Kumar A.M., Tiwari G.N. (1998). Optimization of collector and basin areas for a higher yield for active solar stills. Desalination 116, 1-9. [This communication presents a thermal analysis of an active solar still for the optimization of collectors as well as the basin area for a higher yield for a given water depth.]

Mahmoudi H., Spahis N., Goosen MF., Ghaffour N., Drouiche N., Ouagued A. (2010a). Application of geothermal energy for heating and fresh water production in a brackish water greenhouse desalination unit: a case study from Algeria. Renew Sustain Energy Rev 14, 512–517. [The aim of this paper is to outline new brackish water greenhouse desalination unit powered by geothermal energy for the development of arid and relatively cold regions, using Algeria as a case study.]

Mahmoudi H., Spahis N., Sabah A., Abdul-Wahab S.A.A., Sablani S.S., Goosen M.F.A. (2010b). Improving the performance of a Seawater Greenhouse desalination system by assessment of simulation models for different condensers, Renewable and Sustainable Energy Reviews, in press. [The main objective of this paper is the development of mathematical model for a new proposed passive condenser in order to enhance the performance of a humidification–dehumidification Seawater Greenhouse desalination system]

Mahmoudi H., Ouagued A., Ghaffour N. (2009a). Capacity building strategies and policy for desalination using renewable energies in Algeria. Renew Sustain Energy Rev 13, 921–6. [In this paper, an overview of capacity building strategy and policy for desalination in Algeria is presented].

Mahmoudi H., Spahis N., Goosen M.F.A., Sablani S., Abdul-wahab S., Ghaffour N., (2009b). Assessment of wind energy to power solar brackish water greenhouse desalination units: a case study from Algeria. Renew Sustain Energy Rev 13, 2149–55. [In this study, the potential of using wind energy to drive small scale desalination units in southern Algeria was investigated].


Mortensen L.M. (2000). Effects of air humidity on growth, flowering, keeping quality and water relations of four short-day greenhouse species, Scientia Horticulturae 86, 299-310 [The objective of this study was to evaluate growth, morphology and keeping quality as influenced by air humidity in some flowering greenhouse plants].

Muller-Holst H., M. Engelhardt, W. (1999). Scholkopf, Small-scale thermal seawater desalination simulation and optimization of system design, Desalination 122, 255–262. [This paper presents an optimized distillation method which was originally developed at the University of Munich and which was protected by patent].


humidification–dehumidification processes. Part II. An experimental investigation. *Energy Conversion and Management* 45, 1263–1277. [An experimental investigation of a humidification–dehumidification desalination (HDD) process using solar energy at the weather conditions of Suez City, Egypt, is presented]

Nawayseh N.K., Farid M.M., Al-Hallaj S., Tamimi A.R. (1999a) Solar desalination based on humidification process: I-Evaluating the heat and mass transfer coefficients, *Energy Conversion and Management* 40, 1423–1439. [This paper aims to develop a correlation for the heat and mass transfer coefficient in Humidification Dehumidification units. The developed correlations were used in the second part of this work]

Nawayseh N.K., Farid M.M., Omar A.Z., Sabrin A. (1999b). Solar desalination based on humidification process—II. Computer simulation, *Energy Conversion and Management* 40, 1441–1461. [The main objective of this work was to construct a simulation program that could be used in the design of Humidification Dehumidification Desalination Units].

Nawayseh N.K., Farid M.M., Omar A.Z., Al Hallaj S.M., Tamimi A.R. (1997). A simulation study to improve the performance of a solar humidification-dehumidification desalination unit constructed in Jordan. *Desalination* 109, 277-284. [In this paper an attempt was made to study the possibility of improving the performance of a desalination unit constructed previously in Jordan through a simulation program].

Paton A.C., Davies A. (2006). The seawater greenhouse cooling, freshwater and fresh produce from seawater. The 2nd International Conference on Water Resources in Arid Environments, King Saud University Riyadh 2006. [The seawater greenhouse installed in Oman was presented ]

Paton A.C. (2001). Seawater Greenhouse Development for Oman: Thermodynamic Modeling and Economic Analysis, MEDRC Project 97-AS-005b. [The main objective of this study was to determine the influence of greenhouse-related parameters on a desalination process that combines fresh water production with the growth of crops in a greenhouse system]

Paton C., Davies A. (1997). The seawater greenhouse for arid lands. In: Proceedings of Mediterranean conference on renewable energy sources for water production. [In this paper, the main concepts of the Seawater greenhouse was presented]

Perret J.S., Al-Ismail A.M., Sablani S.S. (2005). Development of a Humidification-Dehumidification System in a Quonset Greenhouse for Sustainable Crop Production in Arid Regions. *Biosystems Engineering* 91 (3), 349-359. [This paper presents a pilot design for a humidification–dehumidification system in a Quonset greenhouse. The objective of this study was to investigate the potential of saline/brackish water evaporation and freshwater condensation to provide an alternative source of freshwater for irrigation in a greenhouse].


Rodriguez L.G. (2001). Seawater desalination driven by renewable energies: A review, *Desalination* 143, 103–113. [This paper deals with seawater desalination systems driven by renewable energies. A review of pilot plants and perspectives of development was presented].


Soufari S.M., Zamen M., Amidpour M. (2009). Performance optimization of the humidification–dehumidification desalination process using mathematical programming. Desalination 237, 305–317. [In this paper the humidification–dehumidification desalination process was studied and its performance optimized using mathematical programming. An advantage of this method was the consideration of simultaneous effect of various parameters on process performance].


Vlachogiannis M., Bontozoglou V., Georgalas C., Litinas G. (1999). Desalination by mechanical compression of humid air. Desalination 122, 35–42. [A novel desalination concept was described, combining the principles of humidification-dehumidification and mechanical vapor compression].

Vorosmarty C.J., Green P., Salisbury J., Lammers R.B. (2000). Global Water Resources: Vulnerability from Climate Change and Population Growth. Science 289, 284-288 [In this paper the situation of water resources and world population growth were discussed].


www.seawatergreenhouse.com [This website presents the different seawater greenhouse projects installed worldwide]

Biographical Sketches

Karim Bourouni, Assistant Professor at the National Engineering School of Tunis (ENIT) and researcher in the Research Unit Energetic in Buildings and Solar System in the same school in Tunisia. He got his graduation in Engineering from ENIT in Industrial Engineering in 1994 and received his PhD in Mechanical Engineering in University of Marseille (France) in 1998. The subject of his PhD was characterization of heat and mass transfer in falling-film, horizontal-tube evaporators used in a small desalination unit functioning by air humidification and dehumidification. Since his PhD, his main research field of interest is the development of small desalination units driven by renewable energies for remote areas. In particular, he focused on humidification dehumidification processes driven by solar energy and Reverse Osmosis coupled to hybrid systems (Wind and Photovoltaic). He coordinates several national and international cooperation projects in the field of desalination and renewable energies (European FP6 projects, AUf, PRF, etc.). He is member in several Desalination Associations (International Desalination Association, European Desalination Society, Tunisian Association of Desalination, etc.) and reviewer for some journals (Desalination Journal, Canadian Journal of Chemical Engineering, etc.). He is author of about 40 publications in refereed journals and several proceedings of international scientific conferences and workshops.

Thameur Chaibi, A Senior Researcher at the National Research Institute for Rural Engineering (INRGREF), water and Forestry, Tunis, Tunisia. Assigned to the program of renewable energies use in rural areas (solar thermal desalination for irrigation, Geothermal water use for heating greenhouses). Responsible for the experimental research station of the INRGREF in "Hazeg" (Eastern coast part of Tunisia). His tasks include coordination of the experimentation protocols, related to field of irrigation systems and water quality improvements in arid area conditions, carried out by the researchers of the institute. He holds his master degree in hydraulic and rural development Engineering from the National Institute of Agronomy in Tunis, June 1987 and prepare his Ph.D. degree at the Uppsala University in Sweden. He coordinates several international projects: project of using geothermal energy, in the southern part of Tunisia (Kebili), for heating greenhouses and producing fresh water for irrigation (SERST/Tunisia, PUGA/Belgium), the project of introducing solar energy applications in rural areas of Tunisia (AOAD : Arab Organization for Agricultural Development, the project of solar drying coffee product in Kagera region of Tanzania. (SIDA Sweden, KARADEA solar facility in Tanzania, the project of optimization and design of geothermal water-cooling towers in the south of Tunisia. (Tunisian Agricultural Ministry), the Project INCO-MED on Policy Initiative to Overcome Water Competition...

Ali Altaee: A researcher in the Environmental engineering, wastewater treatment and water desalination. He finished his PhD at the department of Environmental Engineering in Brighton University, the UK. He did several research studies in water treatment and membrane separation technologies at Brighton University, the University of New South Wales and Surrey University. Then in 2008 he joined Doosan R&D Center in Dubai, UAE. Research interests: Membrane separation technologies, seawater desalination, wastewater treatment and modeling, pollutant transport in soil and aquifers, soil and aquifer treatment and remediation. The author has several papers in seawater desalination, wastewater treatment and soil remediation. He also has few patents in seawater desalination, ion separation, renewable energy methods, and membrane separation processes.