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

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Contents

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:

$$\text{Rate of water loss} = b\,R + c\,D \qquad (1)$$

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:

$$pv = RT_R \tag{2}$$

where

p = pressure of the gas,
v = specific volume of the gas,
R = gas constant,
T_R = 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:

$$P_{at} = p_a + p_w \tag{3}$$

where:

P_{at} = atmospheric pressure of the moist air,
p_a = partial pressure of dry air,
p_w = 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_2O/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):

$$w = \frac{m_w}{m_{da}} = 0.61298 \frac{p_w}{p_{at} - p_w} \tag{4}$$

The *relative humidity* of moist air, φ, 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:

$$\varphi = x_w / x_{ws} \big|_{T,P} = p_w / p_{ws} \big|_{T,P} \tag{5}$$

and

$$x_{\text{w}} = \frac{n_{\text{w}}}{n_{\text{da}} + n_{\text{w}}}; \quad x_{\text{ws}} = \frac{n_{\text{ws}}}{nd_{\text{a}} + n_{\text{ws}}}$$

$$x_{\text{da}} + x_{\text{w}} = 1 \tag{6}$$

Where

p_{ws} = pressure of saturated water vapor,
T = temperature,
$n_{\text{da}}, n_{\text{w}}, n_{\text{ws}}$ = 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:

$$h(T, w) = c_{\text{p.da}}T + w\left(h_{\text{g0}} + c_{\text{p.w}}T\right) \tag{7}$$

where

$c_{\text{p.da}}$, $c_{\text{p.w}}$ = 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:

$$\text{v} = \frac{V}{m_{\text{a}}} \tag{8}$$

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

$$v = \frac{R_{\text{a}}T_{\text{R}}}{P_{\text{at}}\left(1+1.6078w\right)} \tag{9}$$

Moist air density, often called *air density* ρ, 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:

$$\rho = \frac{m_{\text{a}}}{V} = \frac{1}{v} \tag{10}$$

The *sensible heat of moist air* is the thermal energy associated with the change of air temperature between two state points. In Equation (7), $\left(c_{\text{p.da}} + wc_{\text{pw}}\right)T$ indicates the sensible heat of moist air, which depends on its temperature T. *Latent heat of moist air*, often represented by $w \cdot h_{g0}$, is the thermal energy associated with the change of state of water vapor.

$$c_{\mathrm{p.a}} = c_{\mathrm{p.da}} + wc_{\mathrm{p.w}} \quad (11)$$

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 $(T - T_{\mathrm{wb}})$ 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 $(p_{\mathrm{w \times s}}(T) - p_{\mathrm{w}})$, which is the motor term of mass transfer, hence it decreases when $HR = p_{\mathrm{w}} / p_{\mathrm{w \times s}}(T)$ increases.

iv. Psychrometric Charts

Moist air has seven independent thermodynamic properties or property groups: h, T, φ, T_{wb}, p_{at}, $\rho - v$ and $w - p_{\mathrm{w}} - T_{\mathrm{dew}}$. 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.

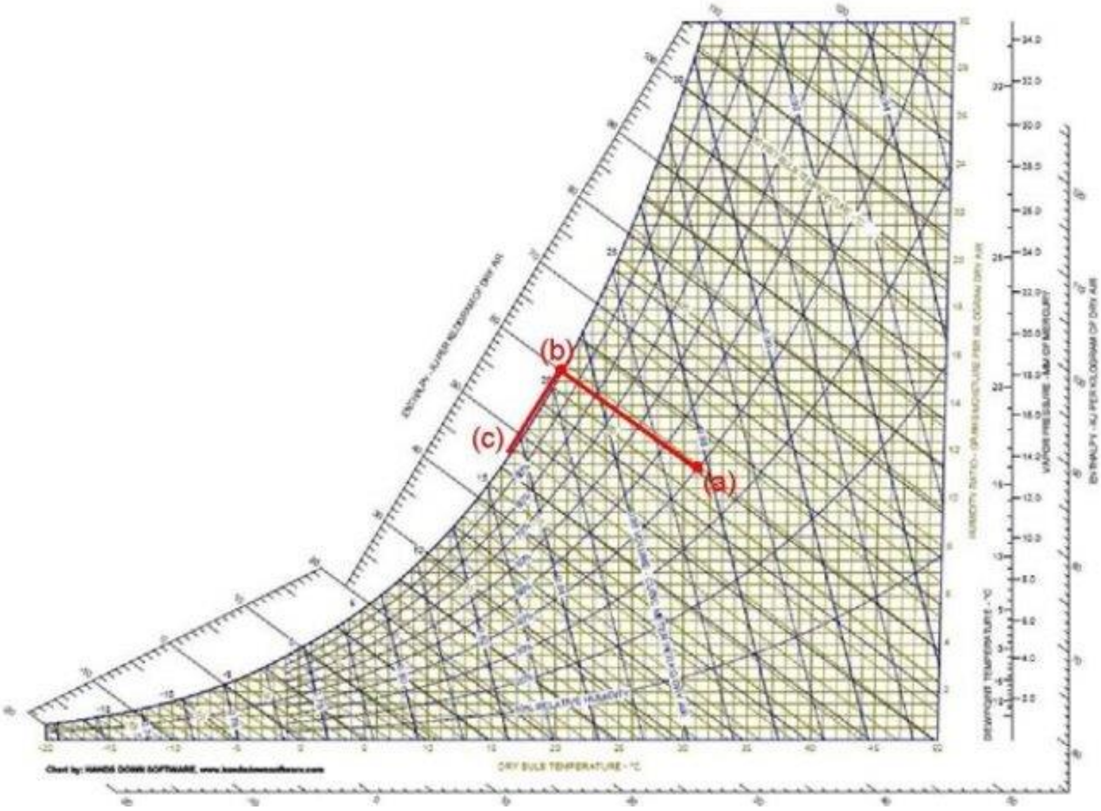

Figure 1. The abridged ASHRAE psychrometric chart: (i) the determination of moist air properties (ii) air properties change in HD process

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:

$$\dot{m}_{\mathrm{hu}} = \dot{V}_{\mathrm{s}} \rho_{\mathrm{s}} \left(w_{\mathrm{out}} - w_{\mathrm{in}} \right) \qquad (12)$$

where $w_{\mathrm{out}}, w_{\mathrm{in}}$ = 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_{we}, determines whether it is a sensible cooling or a cooling and dehumidifying process. If T_{we} is smaller than the dew point of the entering air in the washer, or T_{we} makes the outer surface of the water cooling coil $T_{\mathrm{s\times t}} < T_{\mathrm{dew\times in}}$ it is a cooling and dehumidifying process. If $T_{\mathrm{we}} \geq T_{\mathrm{dew\times in}}$ or $T_{\mathrm{s\times t}} \geq T_{\mathrm{dew\times in}}$ sensible cooling occurs. The cooling coil's load or the cooling capacity of the air washer q_{cc}, is:

$$q_{\mathrm{cc}} = \dot{m}_{\mathrm{s}}\left(h_{\mathrm{a.in}} - h_{\mathrm{a.out}}\right) - \dot{m}_{\mathrm{c}} h_{\mathrm{c}} \tag{13}$$

where
$h_{\mathrm{a.in}}, h_{\mathrm{a.out}}$ = enthalpy of moist air entering and leaving the coil or washer,
$\dot{m}_{\mathrm{c}}$ = mass flow rate of the condensate,
h_{c} = enthalpy of the condensate,

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

$$q_{\mathrm{cc}} = \dot{m}_{\mathrm{a}}\left(h_{\mathrm{a.in}} - h_{\mathrm{a.out}}\right) \tag{14}$$

The sensible heat ratio of the cooling and dehumidifying process SHR_{c} can be calculated from

$$SHR_{\mathrm{c}} = \frac{q_{\mathrm{cs}}}{q_{\mathrm{cc}}} \tag{15}$$

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

SHR_{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 m^3/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).

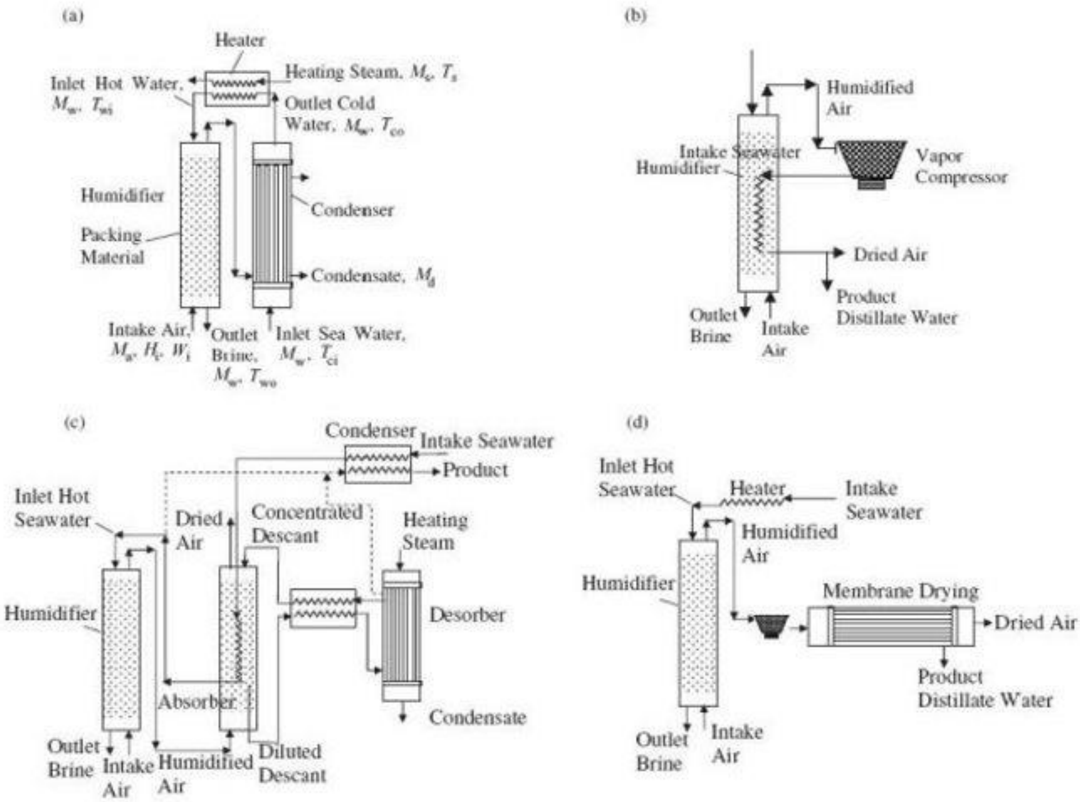

Figure 2. Different layouts of Humidification Dehumidification (HD) process (a) Conventional Humidification Dehumidification process; (b) Humidification vapor compression; (c) Humidification process combined with desiccant material; (d) Humidification and membrane drying, (Ettouney, 2005)

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.

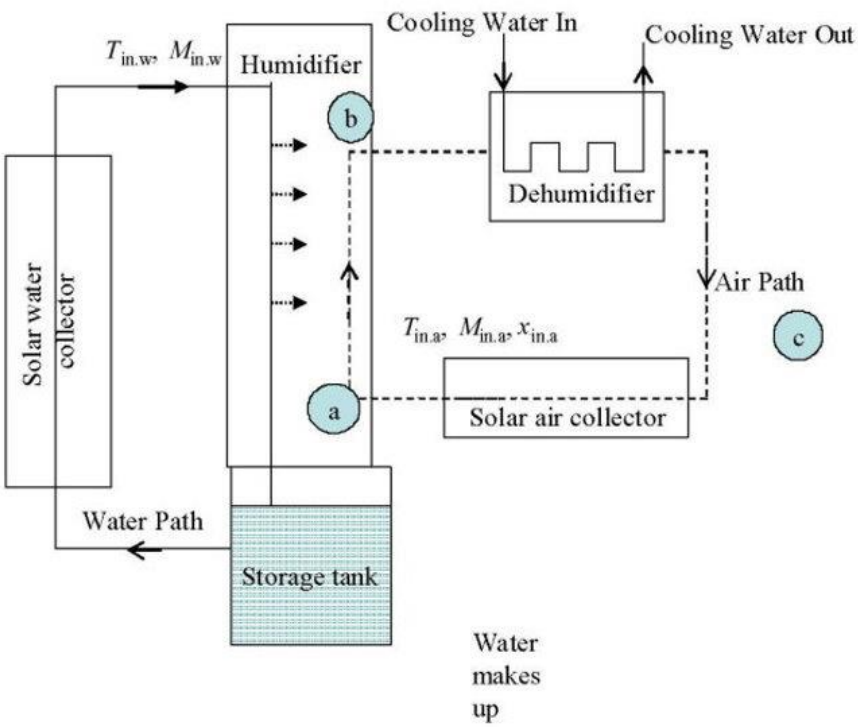

Figure 3. Schematic diagram of (HD) process driven by solar energy, (Nafey et al. 2004a)

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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, Arabic Water Council, 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 referred 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 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 between the Vital Economic Sectors of Agriculture and Tourism in the Mediterranean. He taught in different international training courses in the field of renewable energy applications in rural areas (Damas- Syria-1988, Amman- Jordan- 1993, Malta (1998), Tanzania (2000, 2002).

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.