

Development of Solar Desalination System Using Humidification and Dehumidification Cycle- A Review

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ABSTRACT: Solar humidification-dehumidification desalination technology has been reviewed in detail in this paper. One of the innovative methods for decentralized low-scale purification of water is the humidification-dehumidification (HDH) desalination technology. Many research activities have been carried out recently with the aim of improving this technology. Desalination involves any process in which dissolved minerals are to be removed from saline or brackish water. This paper will give the characteristics for several layouts for the humidification dehumidification desalination process. Paper also gives a brief view to Humidification-Dehumidification (HDH) process by comparing various authors' works. In this paper, mathematical model for energy balance calculation is also reviewed. HDH is a low temperature process where total required thermal energy can be obtained from solar energy. Capacity of HDH units is between that produced by conventional methods and solar stills. Moreover, HDH is distinguished by simple operation and maintenance.

KEYWORDS: Desalination, Humidification and Dehumidification, Solar Air Heater, Humidifier, Dehumidifier & Heat Exchanger.

I. INTRODUCTION

Desalination is a process that removes minerals from saline water. More generally, desalination refers to the removal of salts and minerals from a target substance. The lack of fresh water is a critical issue and risky problem for human beings in future. One of the key approach to overcome this problem is water purification from the available sources like saline water, waste water, industrial and other waste effluents. Different techniques are available in the water purification, which can be classified into single phase processes like Reverse osmosis, Electro dialysis, Membrane distillation and multi phase processes like Multi effect distillation, Flash desalination, Vapour compression desalination, Humidification dehumidification desalination and Solar still[7].

The process based on humidification-dehumidification (HDH) of air principle exactly copied to the natural water cycle. HDH technique has been subject of many studies in recent years due to the possibility of low-temperature energy use such as geothermal, solar, waste energy, it is environmentally friendly, its simplicity, and its low installation and operation costs. Moreover HDH desalination systems work at atmospheric pressure because of this they do not need additional large mechanical energy [2].

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

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Vol. 6, Issue 3, March 2017

1.1 CONVENTIONAL TECHNOLOGIES FOR DESALINATION

There are many technologies for desalination of water. But mainly five Technologies are used for Desalination. They are explained followed:

1.1.1 MULTISTAGE FLASH

Multi-stage flash distillation (MSF) is a water desalination process that distills sea water by flashing a portion of the water into steam in multiple stages of what are essentially counter current heat exchangers. Multi-stage flash distillation plants produce about 60% of all desalinated water in the world [6]. Once through desalination multi stage plant is shown in fig no 1.

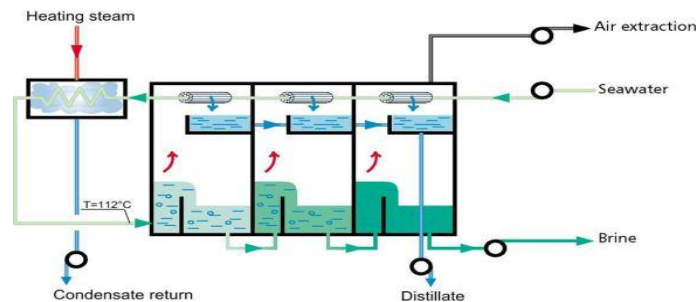


Fig No.1: Once Through Desalination Plant

1.1.2 MULTIEFFECT DESTILLATION

Multiple-effect distillation (MED) is a distillation process often used for sea water desalination. It consists of multiple stages or "effects". In each stage the feed water is heated by steam in tubes. Some of the water evaporates, and this steam flows into the tubes of the next stage, heating and evaporating more water. Each stage essentially reuses the energy from the previous stage. The tubes can be submerged in the feed water, but more typically the feed water is sprayed on the top of a bank of horizontal tubes, and then drips from tube to tube until it is collected at the bottom of the stage [7].

1.1.3 REVERSE OSMOSIS

Reverse osmosis (RO) is a water purification technology that uses a semi permeable membrane to remove ions, molecules, and larger particles from drinking water. In reverse osmosis, an applied pressure is used to overcome osmotic pressure, a colligative property, that is driven by chemical potential differences of the solvent, a thermodynamic parameter. Reverse osmosis can remove many types of dissolved and suspended species from water, including bacteria, and is used in both industrial processes and the production of potable water. The result is that the solute is retained on the pressurized side of the membrane and the pure solvent is allowed to pass to the other side. To be "selective", this membrane should not allow large molecules or ions through the pores (holes), but should allow smaller components of the solution (such as solvent molecules) to pass freely [8].

1.1.4 MEMBRANE DESTILLATION

The process of membrane distillation (MD) has been known since the late 1960 s. In the past decades, MD has gained great development. It has been mostly used in many thermally sensitive industrial processes. It has also been used for waste water treatment and desalination processes. Membrane distillation process can be described as a hybrid process since it combines thermal evaporation and membrane separation principles in a single process unit. A hydrophobic, micro-porous membrane is used in the process. The heated solution contacts with one side of the membrane. Under a certain limiting pressure, the hydrophobic membrane is not wetted by the solution. It means that the membrane prevents the solution from passing through the membrane micro-pores and it only allows the generated vapor to be transferred to the other side [2].

1.1.5 HUMIDIFICATION-DEHUMIDIFICATION DESALINATION(HDD)

solar powered air humidification–dehumidification desalination (HDD) has attracted more and more attention in recent years. Solar energy is a renewable energy source as well as an environmentally friendly energy, which is suitable for the HDD system [13]. The key process is to drive the water vapor from the saline water to air stream, i.e., humidification. This process is commonly realized by packing columns where air and water are in a direct contact. Nafey studied a HDD process driven by solar energy. A solar water heater and a solar air heater are used to heat the water and the air streams respectively. An induced fan cooling tower is used as the humidifying column. Orfi presented a theoretical study of a solar desalination system with humidification dehumidification processes. The basic humidification-dehumidification process is shown in fig no 2.

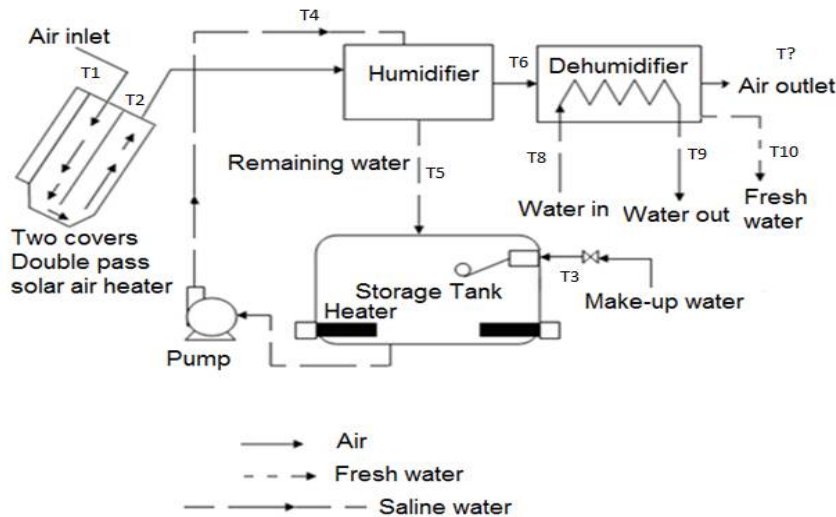


Fig No. 2: HDH System

II. REVIEW OF HDH SYSTEMS

Emrah Deniz and sekan cinar [1] designed novel humidification-dehumidification (HDH) solar desalination system and tested with actual conditions and solar energy was used to provide both thermal and electrical energy. The maximum daily energy efficiency of the system was calculated as 31.54% and the maximum exergy efficiency was found as 1.87%. Jihane, Tahiri, Salouhi and Balli [2] proposed a study of desalination system based on air humidification-dehumidification is investigated theoretically and experimentally. The results obtained from the theoretical model are in very good agreement with those obtained experimentally. Guo-Pei Li, Li-Zhi [3] has given a model on a solar energy driven and membrane based air humidification–dehumidification desalination (MHDD) system is proposed. They designed and constructed to investigate the performance of the system. The test rig consists of a U-tube evacuated solar collector, a heat storage water tank, a membrane-based humidifier (hollow fiber membrane module) and a dehumidifier (a fin and-tube heat exchanger).

A. Khalil, S.A. El-Agouz, Y.A.F. El-Samadony, Ahmed Abdo [4] has given an experimental study of a solar water desalination using an air bubble column humidifier is investigated. They modified the characteristics of the generated bubbles are by using a different sieve plate with different hole size. They studied the effects of water temperature, air flow rate, water height, and sieve's hole diameter on desalination performance is. The results showed that the daily productivity, efficiency and gain output ratio are 21 kg, 63%, and 0.53 respectively; at inlet water temperature is 62 °C. The change in the temperature difference along the column is less than 2.5 °C for all measurements. The best performance is observed from sieve with 1 mm hole diameter at which the outlet air from the bubble columns is always

International Journal of Innovative Research in Science, Engineering and Technology

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saturated. They achieve performance with air bubble column higher than that for the conventional humidifier. Cihan Yildirim, Ismail Solmus [5] investigated the performance of a solar powered humidification–dehumidification desalination system is theoretically for various operating and design parameters of the system under climatological conditions of Antalya, Turkey. They developed mathematical model of the system and governing conservation equations are numerically solved by using the Fourth order Runge–Kutta method. They calculated Daily and annual yields are for different configurations of the system such as only water heating, only air heating and water–air heating. Veera Gnanaswar Gude, Nagamany Nirmalakhandan, Shuguang Deng, Anand Maganti [6] suggested that a low temperature desalination process capable of producing 100 L/d freshwater was designed to utilize solar energy harvested from flat plate solar collectors. Since solar insulation is intermittent, a thermal energy storage system was incorporated to run the desalination process round the clock. Results from this theoretical study confirm that thermal energy storage is a useful component of the system for conserving thermal energy to meet the energy demand when direct solar energy resource is not available. Thermodynamic advantages of the low temperature desalination using thermal energy storage, as well as energy and environmental emissions payback period of the system powered by flat plate solar collectors are presented. It has been determined that a solar collector area of 18 m² with a thermal energy storage volume of 3 m³ is adequate to produce 100 L/d of freshwater round the clock considering fluctuations in the weather conditions. An economic analysis on the desalination system with thermal energy storage is also presented.

Adrian Pugsley, Aggelos Zacharopoulos, Jayanta Deb Mondol, Mervyn [7] Smyth has given global applicability of desalination and proposes a method for correlating international data on water scarcity and stress, saline water resources, and insulation levels, to calculate rank scores ($0 \leq R \leq 1$) which identify where solar desalination is most applicable. Low scores ($R < 0.125$) occur in landlocked nations with limited saline groundwater resources (Nepal, Bolivia, South Sudan) and near polar regions where fresh water is abundant and solar insulation levels are low (Canada, Russia and Scandinavia). High scores ($R > 0.422$) occur in 30 nations, including Middle Eastern and North African countries where fossil fuelled desalination is commonplace, and solar desalination has obvious applicability. They identify 28 further countries (including parts of USA, China, India, Indonesia, Australia, and countries throughout Africa, Asia, South America and Europe) where $0.273 < R < 0.422$ scores indicate that other, less obvious, solar desalination opportunities exist. K. Srithar, T. Rajaseenivasan, N. Karthik, M. Periyannan, M. Gowtham [8] suggested a model of triple basin solar desalination system and proposed a stand-alone triple basin solar desalination system is experimentally tested and the results are discussed in this paper. In their system, mainly consists of a triple basin glass solar still (TBSS), cover cooling (CC) arrangement, parabolic dish concentrator (PDC) and photovoltaic (PV) panel. Four triangular hollow fins are attached at the bottom of the upper and middle basin in order to increase the heat transfer rate and place the energy storing materials. They studied the performance of the system by, conventional TBSS system, integrating the TBSS with CC, TBSS with PDC, and TBSS with CC and PDC. Also, they tested each configuration further by using fins without energy storing material, fins filled with river sand, and fins filled with charcoal. The results of their test reveal that, TBSS with charcoal and TBSS with river sand enhance the distillate by 34.2 and 25.6% higher than conventional TBSS distillates. TBSS with cover cooling reduces the glass temperature to about 8 °C compared to the conventional TBSS. The presence of concentrator increases the lower basin water temperature up to 85 °C. They get maximum distillate yield of 16.94 kg/m².day is obtained for TBSS with concentrator, cover cooling and charcoal in fins.

A. ENERGY ANALYSIS:

Energy analysis done by Yildirim and Solmus has made some following assumptions to simplify the calculations [13].

- Solar radiation, wind speed and relative humidity & temperature of the ambient air are constant at each instant through an hour.
- There are no air leakage from the system, when air passes through the solar air heater & humidifier and dehumidifier.
- Cooling water temperature is constant through out the operation.

From Schematic Diagram of HDH system as shown in Fig no 2:

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For Dehumidifier:

$$m_a (h_6 - h_7) = m_{cw} C_{pw} (T_9 - T_8) - m_{dw} C_{pw} T_{10} \quad (1)$$

Humidifier Energy balance is,

$$m_w C_{pw} (T_4 - T_5) = m_a (h_6 - h_2) \quad (2)$$

The moisture content of air at Solar Air Heater can be calculated as[1];

$$W_1 = \frac{0.622 \phi P_g}{P - \phi P_g} \quad (3)$$

where P_g is vapor saturation pressure and it is calculated as,

$$P_g = 2.7 \times 10^{-9} T^5 + 2.8 \times 10^{-7} T^4 + 2.7 \times 10^{-5} T^3 + 0.0014 T^2 + 0.044 T + 0.61 \quad (4)$$

Where h_{fg} is saturated water vapors enthalpy and can be given as;

$$h_{fg} = -9.3 \times 10^{-6} T^3 - 1.9 \times 10^{-5} T^2 + 1.8 T + 2500 \quad (5)$$

The humidity and enthalpy of saturated air are functions of air temperature and can be calculated as;

$$w = 7.7 \times 10^{-7} T^3 - 1.95 \times 10^{-5} T^2 + 0.00071 T + 0.002 \quad (6)$$

$$h_a = 2.82 \times 10^{-5} T^4 - 0.00106 T^3 + 0.00615 T^2 + 1.32 T + 10.5 \quad (7)$$

The difference of moisture contents of dehumidifier unit inlet and outlet is used to calculate mass flow rate of produced clean water leaving dehumidifier.

$$m_c = m_a (w_3 - w_4) \quad (8)$$

2.2. System Performance:

The most commonly used performance indicators for desalination systems are; the gained output ratio (GOR), performance ratio and system efficiency.

2.2.1. Gained Output Ratio

The gained output ratio is used for describing the effectiveness of water production of thermal desalination process which is also defined as an energy ratio or a mass ratio. GOR is calculated by an Eqn[1];

$$GOR = m_{ew} L / Q_{in} \quad (9)$$

Where “ Q_{in} ” is the energy input to the desalination system from solar systems. Also “ L ” is the latent Heat of Vaporization (J/kg), “ m_{ew} ” is hourly output of solar HDH system (Kg/h).

2.2.2. Overall System Efficiency

The energy required for distilled water production depends on latent heat of vaporization and can be written as[1],

$$E_{dw} = m_{ew} L \quad (10)$$

The performance of HDH desalination system which also means the energy efficiency is calculated as latent heat of vaporization of distilled water divided by heat input to the system;

$$\eta = m_{ew} L / Q_T \quad (11)$$

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where Q_T is the total energy input from PV panel, water & air heater[1].

The energy balance in condenser (dehumidifier) written as follows[2]:

$$Q_{\text{entering}} = Q_{\text{leaving}} + Q_{\text{loss}} \quad (12)$$

Where Q represents a heat rate. Heat enters to condenser via humid air with mass flow rate G , and with an enthalpy H_6 , in addition, heat enters through the seawater flow rate L at temperature T_8 . Thus:

$$Q_{\text{entering}} = mH_6 + LC_p T_8 \quad (13)$$

Heat leaves the condenser through air and water flows. Leaving air is not saturated at temperature T_7 , thus its heat content is mH_7 , water leaves at temperature T_9 , higher than T_8 due to heat exchanging process.

$$Q_{\text{leaving}} = mH_7 + LC_p T_9 \quad (14)$$

Condenser heat loss is calculated with an overall approach, considering an average temperature T_{avgc} of the system ($T_{\text{avgc}} = (T_6 + T_7)/2$), over the ambient temperature T_{amb} , the external area envelop A_c , and an overall heat transfer coefficient U_{LC} :

$$Q_{\text{loss}} = U_{LC} A_c (T_{\text{avgc}} - T_{\text{amb}}) \quad (15)$$

Then Substituting Eqs. (15), (14) & (13) in Eq. (12)

$$(mH_6 + LC_p T_8) - (U_{LC} A_c (T_{\text{avgc}} - T_{\text{amb}})) - (mH_7 + LC_p T_9) = 0$$

which can be rearrange as:

$$m(H_6 - H_7) + LC_p (T_8 - T_9) - U_{LC} A_c (T_{\text{avgc}} - T_{\text{amb}}) = 0 \quad (16)$$

The heat transfer rate in the dehumidifier is written:

$$LC_p (T_8 - T_9) = U_{\text{cond}} A_{\text{cond}} [(T_6 - T_5) - (T_2 - T_8) / \ln [(T_6 - T_5)/(T_2 - T_8)]] \quad (17)$$

In similar way following equation Eq. (12), and the average temperature T_{avgH} of the system ($T_{\text{avgH}} = T_4 + T_5 / 2$), the heat balance in the humidifier is as follows:

$$(mH_2 + LC_p T_4) - (mH_6 + LC_p T_5) - (U_{LH} A_H (T_{\text{avgH}} - T_{\text{amb}})) \quad (18)$$

which can be rearrange as:

$$m(H_2 - H_6) + LC_p (T_4 - T_5) - U_{LH} A_H (T_{\text{avgH}} - T_{\text{amb}}) = 0 \quad (19)$$

The mass transfer rate in the humidifier is written as:

$$m(H_2 - H_6) = KaV [(H_6 - H_4) - (H_2 - H_5) / \ln [(H_6 - H_4)/(H_2 - H_5)]] \quad (20)$$

NOMENCLATURE:	
C_p	specific heat (kJ/kg K)
E_{dW}	energy required for distilled water (W)
G	global radiation (W/m ² K)
h_a	enthalpy of ambient air (kJ/kg K)

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h_2	enthalpy of air at SAH outlet (kJ/kg)
h_6	enthalpy of air at dehumidifier inlet (kJ/kg)
h_7	enthalpy of air at dehumidifier outlet (kJ/kg)
L	latent heat of vaporization (J/kg)
m	mass flow rate (kg/s)
m_{ew}	hourly yield/output of solar HDH system (kg/h)
Q	T total heat input of the system (W)
SAH	solar air heater
T	ambient temperature (K)
w	moisture content of air ($\text{kg}_{\text{water}}/\text{kg}_{\text{air}}$)
w_1	moisture content of the air at SAH inlet ($\text{kg}_{\text{water}}/\text{kg}_{\text{air}}$)
w_3	moisture content of air at dehumidifier inlet ($\text{kg}_{\text{water}}/\text{kg}_{\text{air}}$)
w_4	moisture content of air at dehumidifier outlet ($\text{kg}_{\text{water}}/\text{kg}_{\text{air}}$)
U_{cond}	Overall coefficient of heat transfer at condenser, $\text{J/s m}^2 \text{ } _\text{C}$
H	Enthalpy J/kg
L	Brine mass flow rate, kg/s
V	Tower volume, m^3
a	Evaporator substratum specific area, m^2/m^3
U_{LC}	Overall heat loss coefficient in condenser, $\text{J/s m}^2 \text{ } _\text{C}$
SUBSCRIPTS:	
1	air heater input
2	air heater output
3	water heater input
4	water heater output
5	waste water outlet from the humidifier
6	saturated vapor inlet to the condenser
7	dehumidified air from the condenser
8	cooling water inlet to the condenser
9	cooling water outlet from the condenser
10	clean water temperature at outlet the of dehumidifier
a	air and ambient
ah	air heater
c	collector and clear water
cw	cooling water
da	dry air
dw	distilled water
g	glass cover

III. CONCLUSION

The HD process presents a very interesting solution for small units like hotels, rural regions, light industry, etc, especially when new materials are used. The process is very convenient in cases where heat is available at low temperature at cheaper cost (cogeneration, solar energy, geothermal energy, etc.)[5]. A collector with a double glazing, a highly roughened absorber, and a carbon black coated absorber, results in a collector efficiency of 58% [3]. It is necessary to obtain the best design and operating conditions that give the minimum product cost.

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