© 2018 IJSRST | Volume 4 | Issue 5 | Print ISSN: 2395-6011 | Online ISSN: 2395-602X
Themed Section: Science and Technology

Humidificaton-Dehumidification Desalination System - An Overview

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ABSTRACT

This article reports about the recent researches and modifications carried out in the humidification-dehumidification desalination system using renewable energy sources, waste heat recovery and combined desalination systems for improving the fresh water production rate. Major desalination processes consume a large amount of energy derived from oil and natural gas for heat and electricity, while emitting harmful gases. Solar desalination has emerged as a promising renewable energy-powered technology for producing fresh water. Also, recovering waste heat from various heat sources is considered an economical one. Combining the principle of humidification-dehumidification with solar desalination results in an increase in the overall efficiency of the desalination plant. A brief study of the mechanism of various advancement in the humidification-dehumidification desalination system is presented in this report, along with an economical evaluation of the process. Comparison of the efficiencies and costs of currently available various humidification-dehumidification desalination processes presented in this report. The three major components such as humidifier, dehumidifier, and heater of the humidification–dehumidification desalination unit are undergone simulation verification and design optimization.

Keywords: Solar Desalination; Hybrid Systems; Waste Heat Recovery; Humidification–Dehumidification; Economics

I. INTRODUCTION

Notations

a Specific area (m2/m3)
A area(m^2)
C_p specific heat capacity at constant pressure (J/kg K)
CF conversion factor
$\dot{D}$ production rate
d_p mean particle diameter [m]
G_m freshwater yield (kg/h)
$G_{m,\,all}$ all-day freshwater yield of the system (kg)
G^*_m freshwater yield of unit collecting area (kg/(hm2))
h specific enthalpy, (kJ/kg)
h_{fg} latent heat of vaporization
k Thermal conductivity (W/m·°C)
k' Mass transfer coefficient (kg/m2·s)
k_0 parameter in Toth equation [mol kg–1 bar–1]
k' Mass transfer coefficient (kg/m2·s)
L fixed bed length [m]
$\dot{m}$ mass flow rate
n parameter in Toth equation [–]
no number of collecting units in the system
P power input to air blower and water pumps, (Wh)
p pressure
Q heat flux
R universal gas constant [kJ mol–1 °C–1]
t time(s)
T Temperature, °C
u gas superficial velocity [m s–1]

U overall heat transfer coefficient

Z axis

Subscripts

0 dead state (ambient)

a humid air

amb ambient

ave average

b brine

c condensation

cond condenser

cpc compound parabolic concentrator

cs cold stream

cw cooling water

d dehumidifier

da dry air

e evaporation

evap evaporator

f feed water

h humidifier

hs hot stream

ht heater

in inlet

loss heat loss

local defined locally

max maximum

opt optimum

out outlet

p pumping

pw pure water

sl solar collector

st storage tank

u useful

w water

Greek letters

η efficiency

Δ difference

θ dimensionless temperature difference

ξ fixed bed voidage fraction [–]

ε energy based effectiveness (–)

Ψ enthalpy pinch (J/kg dry air)

ρ_f gas phase density [kg m–3]

μ_f gas phase viscosity [kg m–1 s–1]

Ψ_{TD} terminal enthalpy pinch (J/kg dry air)

λ Latent heat (J/kg)

ω humidity ratio, kg_w/kg_{da}

ω^* equilibrium adsorption capacity [mol kg–1]

ω_s saturation adsorption capacity [mol kg–1]

II. INTRODUCTION

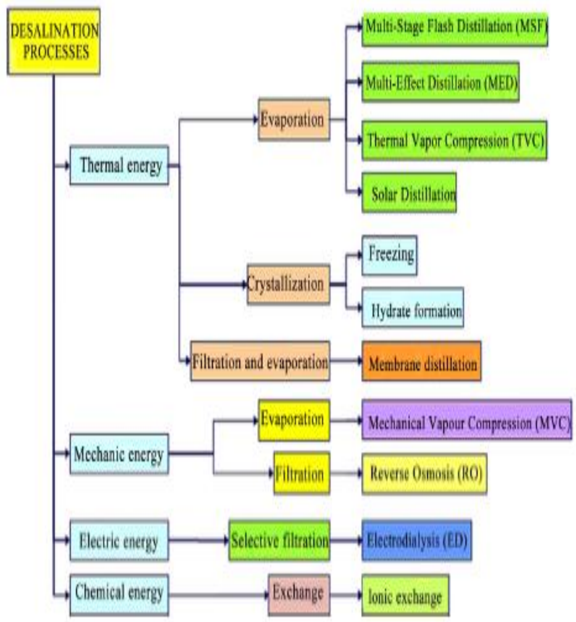
The fresh water scarcity, energy crisis, and climate change are the most intimidating concerns for mankind as it brought many disquiets like health, pollution, and environmental issues. The problem is more severe in developing countries where the population growth projection is much higher as compared to developed countries. The increase in world population growth results in high demand for potable water that is predicted to be 6,900 billion m3 by 2030. The existing supply of fresh water is 4,200 billion m3 that is well below the projection of potable water demand. The challenge is to provide sustainable solution to balance the potable water requirements by secure and affordable energy with the pressing issue of climate change. Water is one of the most abundant resource present on earth. However, around 97.5 % of the earth water is saline, leaving behind approximately 2.5 % fresh water. Major part of the fresh water is hard to access as it is frozen as icecaps and glaciers. Therefore, little quantity of fresh water is available to support our lives. However, rapid population growth have resulted in higher fresh water demand for domestic as well as agriculture sector to produce adequate quantities of food. While the fresh water demand is rising exponentially, the industrial revolution is making the fresh water scarcity situation more alarming by polluting the lakes and rivers by industrial waste. Keeping in mind the aforementioned concerns, the number of people affected by clean water scarcity are expected to escalate four times over the next 25 years. Given the fact that the population on earth continues to increase and industrial growth shows no signs of slowing down, it is inevitable that conventional sources of freshwater are not sustainable.

To eliminate this threatening theme and the trepidations of the existing and approaching crisis, the answer for sustainability may lie in decentralized small scale water desalination.

III. DESALINATION PROCESSES

Different types of water desalination processes have been developed. Figure 1 illustrates the different types of desalination processes. The desalination processes can be mainly classified into the following two categories: phase change (thermal processes) and single phase (membrane processes).

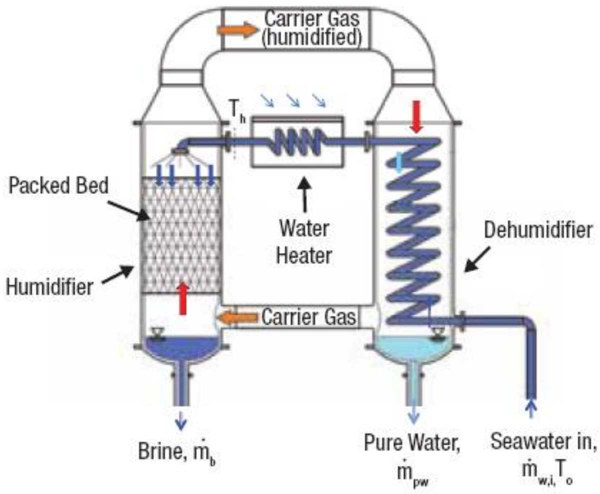
In the phase change process a thermal energy source, such as fossil fuels, nuclear energy or solar energy may be used to evaporate water, which is condensed to provide fresh water. The phase change desalination processes described here include, solar distiller, Multi-Stage Flash (MSF) distillation, Multi-Effect (ME) distillation, Vapor Compression (VC) distillation and Freezing distillation. In the single phase processes membranes are used in two commercially important desalination processes, Reverse Osmosis (RO) distillation and Electro Dialysis (ED) distillation.



Figrue 1. Different types of desalination processes

IV. HUMIDIFICATION DEHUMIDIFICATION DESALINATION TECHNOLOGY

HDH is a distillation technology which operates using air as a carrier gas to shuttle vapor and energy between the evaporation and condensation processes. The simplest version of this technology has a humidifier, a dehumidifier, and a heater to heat the seawater stream. Several other embodiments of the system are possible based on the various classifications of the HDH system listed by Narayan et al. [1]. One of those embodiments incorporates mass extractions and injections in the system to continuously vary the water-to-air mass flow rate ratio along the humidifier and the dehumidifier. A schematic diagram of an HDH system with a single mass extraction and injection is shown in Figrue 2. The system shown is a water-heated, closed-air, open-water (CAOW) system with a single air extraction from the humidifier into the dehumidifier.



Figrue 2. Humidification-dehumidification desalination

V. CLASSIFICATION OF HDH SYSTEMS

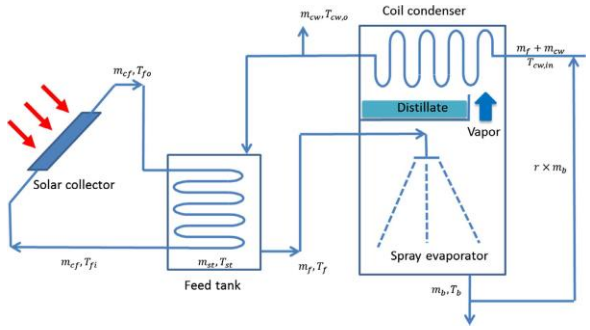
HDH systems are classified under three broad categories according to type of energy used, cycle configuration, and type of heating systems. HDH systems can be classified based on the form of energy used such as solar, thermal, geothermal, or hybrid systems. These classification of the HDH desalination principle brings out the most promising merit and the promise of water production by use of low grade energy, especially from renewable resources. Based on the cycle configuration HDH systems are classified, into closed air open water, closed water or open air open water systems. In all these configurations the flow can be either forced or natural [1].

1. Closed-Air Open-Water (CAOW) Water Heated Systems
2. Multi Effect Closed-Air Open-Water (CAOW) Water Heated System
3. Closed-Water Open-Air, Water Heated (CWOA-WH) System
4. Closed-Air Open-Water Air Heated (CAOW-AH) Systems
5. Open-Air, Open-Water, Air-Heated (OAOW-AH) Systems
6. Open-Air, Open-Water, Water Heated (OAOW-WH) Systems

VI. DIFFERENT MODIFICATIONS AND ANALYSIS IN HDH SYSTEM

A. Q.Chen [2]

This proposed model had brought out a solar powered low temperature desalination system. The system consists of a spray evaporator, a coil condenser, a feed tank and a flat plate solar collector. Here the hot feed water from the feed tank is injected into the spray evaporator which is under vacuum.



Figrue 3. solar powered spray assisted desalination

Differing from the HDH cycles that operate under atmospheric conditions, the spray-assisted low-temperature desalination system uses evaporators and condensers that operate under low-pressure conditions. Accordingly, the evaporation rate is higher due to a larger driving force. Additionally, the hot seawater breaks into smaller droplets due to the flash atomization effect.

The thermal efficiency is expressed as the ratio of the equivalent evaporative energy of the distillate to the thermal energy gained from the solar collector and is shown in Eqn(1).

$$\eta_T = \frac{\int \dot{D} h_{fg} dt}{\int \dot{m}_{cond,f} c_p (T_{fin} - T_{fout}) dt} \qquad (1)$$

B. Shuang-Fei Li [3]

Shuang-Fei Li has constructed a solar desalination system with multi-effect heat recovery processes using all-glass evacuated tube absorber as heat collector, in which there is no usage of electrically operated pump. The steam and freshwater flow are driven only by pressure drop, was designed and tested. Here the whole system consists of 7 heat collecting/heat recovery integration units, which were divided into 7 temperature/pressure states and each unit has a heat collector which consists of a simplified CPC panel, an all-glass evacuated tube absorber, a seawater tank and a bar heat pipe that connects the absorber and seawater tank to transfer heat from the absorber to the seawater tank.

In this experimental system, the steam temperatures, the wall temperatures of heat pipe, the temperatures of steam/water mixture inlet and outlet were measured for investigating both the solar collecting and heat recovery performances.

The instantaneous value of the freshwater yield of unit collecting area is obtained by Eqn(2).

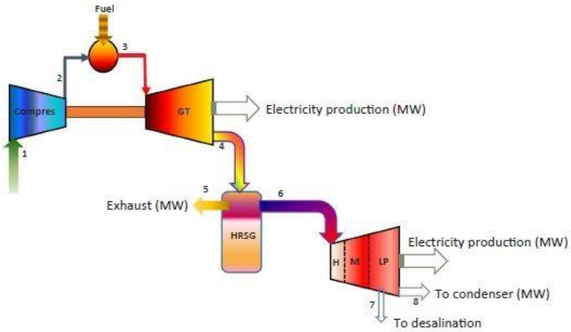
$$G_m^* = \frac{G_m}{A_{cpc} \times no} \qquad (2)$$

Figrue 4. solar seawater desalination system with 7 collecting units.

C. Muhammad Wakil Shahzad, [4]

In this proposal the solution for the need of (i) appropriate primary fuel cost appointment method for multi-purposed plants and (ii) desalination processes performance evaluation method based on primary energy have been provided that is ,the exergetic analysis for primary fuel percentage apportionment to all components in the cycle according to the quality of working fluid utilized. The proposed method showed that the gas turbine was under charged by 40%, steam turbine was overcharged by 71% and desalination was overcharged by 350% by conventional energetic apportionment methods.

In a combined cycle gas turbine (CCGT) and desalination plants, high pressure steam produced in heat recovery steam generator (HRSG) by circulating high temperature burnt gases as shown in the Figrue 5, perform two important tasks such as: (i) the mechanical work generation by expanding in turbines that drives the electric generators for electricity production and, (ii) the extracted steam from the low-pressure turbines, utilized in desalination systems such as multi effect desalination (MED) and multi stage flash (MSF) to produce fresh water.



Figrue 5. CCGT and HRSG desalination

Also a new and most suitable desalination processes performance evaluation method based on primary energy, called universal performance ratio (UPR) shown in Eqn(3).

$$UPR = \frac{evaporative\ energy}{primary\ enrgy\ input}$$

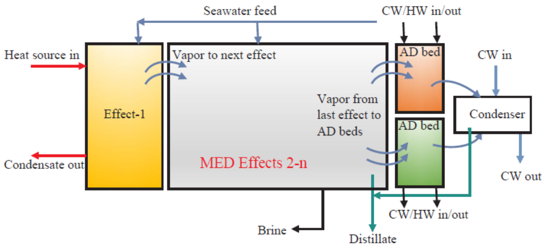
$$= \frac{h_{fgvapour}}{3.6\left\{CF1\left(\frac{kWh}{m^3}\right)_{electrical} + CF2\left(\frac{kWh}{m^3}\right)_{thermal} + CF3\left(\frac{kWh}{m^3}\right)_{renewable}\right\}}$$

(3)

where hfg vapor is equivalent vapor energy, CF1 is the conversion factor for electricity to the primary energy, CF2 is the conversion factor for thermal input to the primary energy and CF3 for renewable to primary energy. The kilo-watt hour per cubic meter (kW h/m3) is the specific energy consumption in terms of electrical, thermal and renewable. The conversion factors are calculated on the basis of exergy destruction across the components corresponding to primary fuel exergy.

MED hybridization with AD cycle have made a great strike towards improving the efficacy of practical desalination methods. The hybridization of the conventional MED method with the adsorption (AD) desalination cycles has been extensively investigated. The AD cycle is attached to the bottom-brine stage of the MED, acting as a vapor compressor to lower the bottom-brine temperature of MED. The detail schematic of hybrid MEDAD cycle is presented in

Figrue 3 where last stage of MED is combined with AD cycle to break lower brine temperature.

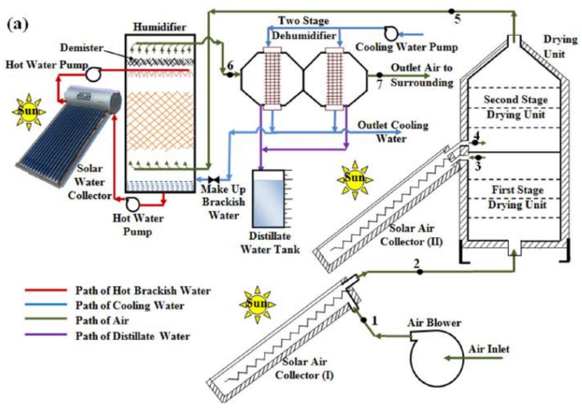


Figrue 6. MED+AD hybrid cycle detailed flow schematic.

D. A.E. Kabeel [5]

A.E. Kabeel studied the performance and experimentally investigated a two-stage indirect solar dryer with reheating coupled with humidification-dehumidification (HDH) seawater desalination systems.

The proposed system consists of two sub-systems: (i) two-stage indirect solar dryer with reheating, which can use to remove the moisture contents from the plants and fruit; (ii) the HDH water desalination, which can use to production of distillate water. Figrue 7 shows the schematic diagram and a photo of a two stage indirect solar dryer with reheating coupled with humidification dehumidification water desalination systems.



Figrue 7. Two-stage indirect solar dryer with reheating coupled with HDH water desalination system

Use a two-stage dryer with reheating improved the moisture removal from the product by 71.78% in average as compared only to the first stage of drying unit.

The gain output ratio (GOR) of the desalination system is expressed as given in Eqn(4).

$$GOR = \frac{\Sigma\,(\dot{D}*h_{fg})}{\Sigma\,(Q_{sun}+P)} \qquad (4)$$

The gain output ratio varies over ranges of 1.24–1.79 and 0.97–1.38 for the proposed system and the HDH desalination system only, when the airflow rate increases from 50 to 75 m3/h.

The overall gain output ratio (OGOR) of the proposed system is defined as the ratio of the sum of latent heat required to evaporate the moisture from the product in the drying unit plus the latent heat required to evaporate the distillate water in the humidifier to the total energy input into the proposed system. It is expressed as follows:

$$OGOR = \frac{\Sigma(\dot{D}\times h_{fg})+\Sigma(\dot{m}_a(\omega_{entering}-\omega_{leaving})\times h_{fg})}{\Sigma(Q_{sun}+P)} \qquad (5)$$

E. Efaf Z. Mahdizade [6]

Efaf Z. Mahdizade developed a SOAOW humidification-dehumidification (HDH) seawater desalination system for both water-heated system and air-heated system, when the top temperature of the system is fixed, this method for air circulation can enhance the performance of the system. Other parameters are analyzed and they reveal that the impact of ambient temperature is more important than that of the ambient relative humidity on system performance.

The entropy generation of both humidifier and dehumidifier are calculated to ensure the possibility of the process of desalination by the system. Due to the mass transfer between air and water in humidifier and condensation of pure water in dehumidifier, the effectiveness is a function of both temperature and humidity. The effectiveness of humidifier and dehumidifier is defined in the Eqn(6).

$$\varepsilon = \frac{\Delta H}{min(\Delta H_{max,w}, \Delta H_{max,a})} \quad (6)$$

The performance of an HDH system is commonly known as gained output ratio (GOR), which is the ratio of the latent heat of evaporation of the water produced to the heat input to the system is represented in the Eqn (7)

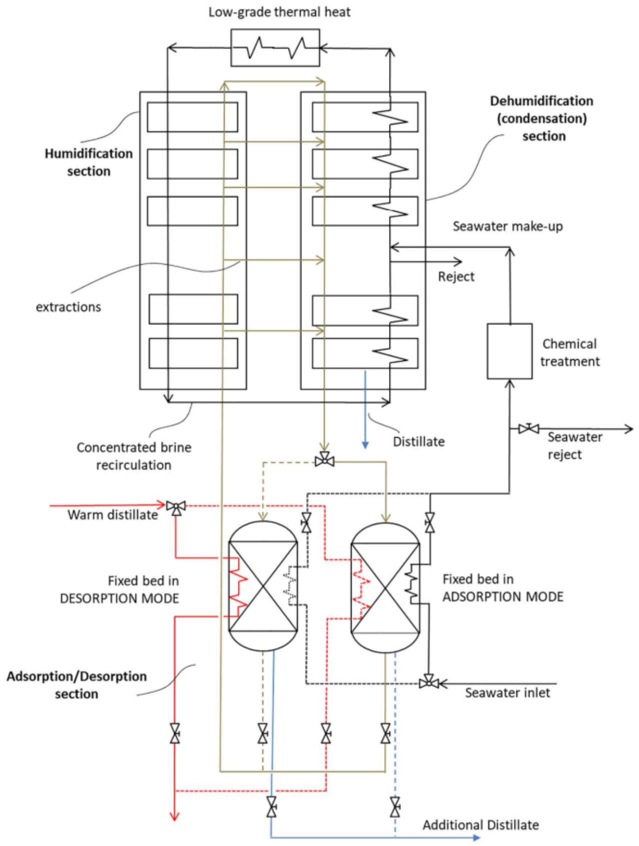
$$GOR = \frac{\dot{m_{pw}} h_{fg}(T_o)}{\dot{Q}_{in}} \quad (7)$$

$$\dot{Q}_{in} = \dot{m}_h (h_{ht,out} - h_{ht,in}) \quad (8)$$

Here the effect of each parameter on semi-open air, open water humidification-dehumidification desalination with water or air heating is analyzed. As long as the top temperature of the system is fixed, the generated entropy within the solar collector is almost fixed too, because the variation of returned air form dehumidifier does not cause a significant change to the temperature difference of heated flow which means nearly constant inlet heat is needed .

F. M. Capocellia [7]

M.Capocellia analyzed a novel process scheme consisting of a multiple extraction humidification-dehumidification with vapour adsorption (HDHA) and brine recirculation. This process can be considered a closed-air closed-water (CACW) HDH works with bottom brine temperatures below the coldest heat source and direct recirculation.



Figrue 8. HDHA Desalination

The novel Humidification-Dehumidification scheme that implements an air drying stage through vapour adsorption coupled with a twin regeneration column as shown in Figrue 8.

A mathematical modelling of this system has been developed and the effects of air humidity and number of stages/extraction has been proposed.

The adsorption equilibrium for the water vapour-silica gel system is described according to the Toth isotherm:

$$\omega^* = \frac{k_o exp\left(\frac{\Delta H_{ads}}{RT}\right) P_{H_2o}}{\left\{1+\left[\frac{k_o}{\omega_S} exp\left(\frac{\Delta H_{ads}}{RT}\right) p_{H_2O}\right]^n\right\}^{\frac{1}{n}}} \quad (9)$$

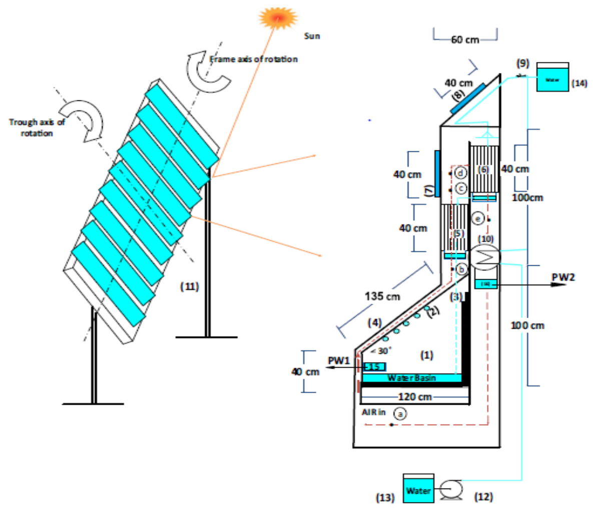
The relationship between the total pressure gradient across the adsorption column and the gas superficial velocity can be derived from the Ergun equation:

$$\frac{\Delta p}{L} = \frac{1.50\times10^{-3}\mu_f(1-\xi)^2}{\xi^3 d_p^2} u + \frac{1.75\times10^{-5}(1-\xi)\rho_f}{\xi^3 d_p} u^2 \quad (10)$$

According to the simulation results obtained from this system, the lower the humidity entering the humidification unit, the higher the thermodynamic performances of the HDHA; the higher the number of extractions, the lower the energy footprint (GOR up to 10) and reported the basic design for the potentiality of 30 m3 day−1 of distilled water with high performances (GOR of 7 and a RR of 50%) obtained in a 4-stage HDHA by fixing the relative humidity of the air exiting from the adsorption unit at 20.

G. Amir Mahmoud [8]

Amir Mahmoud constructed and evaluated the performance characteristics of a solar desalination system by means of hybrid solar still and two effects humidification-dehumidification seawater desalination system combined with solar concentrator and two thermally cooled PV panels, one for electrical energy and another to preheat feed water feeding the second humidifier.



Figrue 9. Hybrid solar still HDH desalination system

The performance characteristics of the system is evaluated under different operating conditions such as varying the basin water height, circulating air mass flow rate, and solar concentration ratio. Photovoltaic panels are integrated along with solar concentrator leads to a significant increase in the fresh water yield at high concentration ratio. The integrated SS-HDH-PV/T system includes closed circulating air and water loops.

Mass flow rate of water:

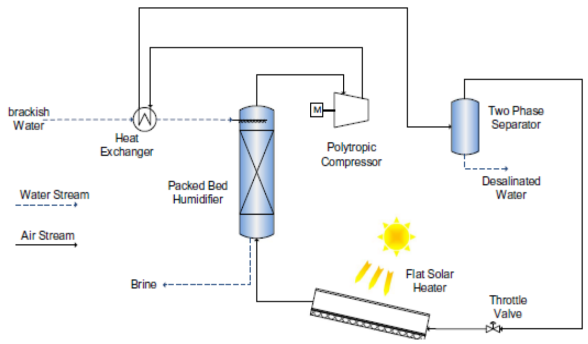
$$m_{pw} = \frac{Q_{cond}}{(T_{out}-T_{in})\times Cp_{pw}} \quad (11)$$

Useful energy:

$$Q_u = m_{fluid} \times c_{fluid} \times \left(T_{fluid_{out}} - T_{fluid_{in}}\right) \quad (12)$$

H. Younes Ghalavand [9]

Younes Ghalavand investigated the operational characteristics of the humidifier in a solar driven humidification-dehumidification desalination system where dehumidification is carried out by compression. He also developed a mathematical model to investigate the effect of operating conditions of humidifier. The mathematical model with insulation effect the model precision increases compared to the model without insulation effect and the absolute error is decreased up to 2.4% based on experimental data. A process flow diagram of Compressor combined HDH desalination system process is shown in Figrue 10.



Figrue 10. Compressor combined HDH desalination system

$$m_a \frac{d\omega}{dZ} = a\frac{\pi d^2}{4} k'_{w-a}(\omega^* - \omega) \quad (13)$$

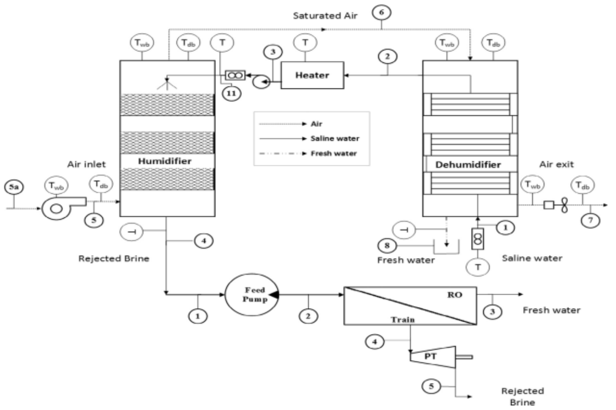
$$\frac{dm_w}{dz} = m_a \frac{d\omega}{dZ} \quad (14)$$

$$m_w Cp_w \frac{dT_w}{dz} + T_w Cp_w \frac{dm_w}{dz} = a\frac{\pi d^2}{4} h_{w-a}(T_w - T_{air}) + a\frac{\pi d}{4} k'_{w-a}(\omega^* - \omega)\lambda \quad (15)$$

The Eqn(13-15) are solved by numerical methods to predict the humidity, water temperature and air temperature in humidifier.

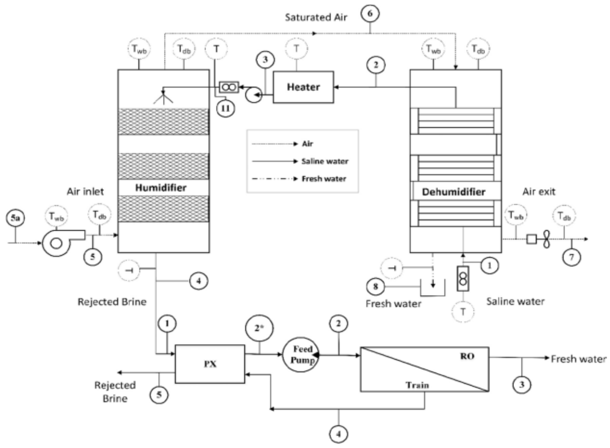
I. Muhammad Ahmad Jamil [10]

Muhammad Ahmad Jamil made an exergo-economic investigation of humidification-dehumidification seawater desalination system operating under a conventional OWOA and a modified CWOA configuration and the hybrid HDH-RO system under three different retrofits including a simple HDH-RO, HDH-RO with a Pelton turbine as shown in Figure 11 and HDH-RO with a pressure exchanger as shown in Figrue 12.



Figrue 11. Hybrid HDH-RO with pelton turbine desalination system

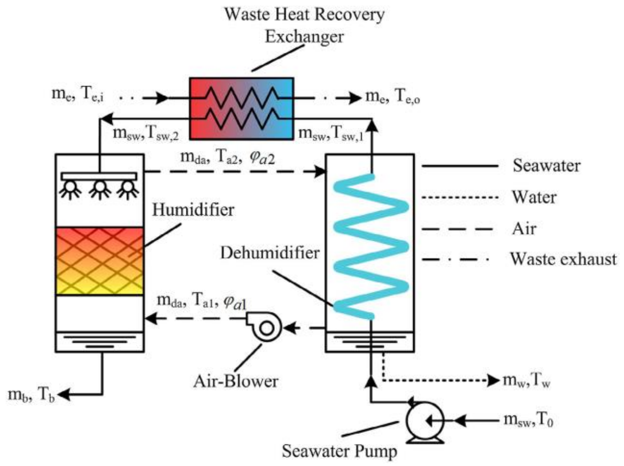
The hybrid systems stated above are analyzed in terms of GOR and exergetic efficiency and the economic analysis was performed by two methods (i) El-Dessouky et al'(ii) cost flow method. Through these method various results have been obtained and they are considered to be better. From those results it is said that the modified cycle (CWOA) has a higher exergetic efficiency and lower product cost than the basic cycle (OAOW). Coupling HDH systems with a renewable energy enhanced its economic performance and tackled its main issue of high energy requirement. The product cost for hybrid HDH-RO using electrical heater is estimated to be $0.11/m3 (El-Dessouky method) and $0.13/m3 (cost-flow method). The product cost when the system utilized solar heater turned out to be $0.11/m3 (El-Dessouky method) and $0.12/m3 (cost-flow method).



Figrue 12. Hybrid HDH-RO with pressure exchanger desalination system

J. W.F. He [11]

W.F. He made use of seawater to recover the waste heat in the humidification-dehumidification desalination system as shown in the Figrue 13.



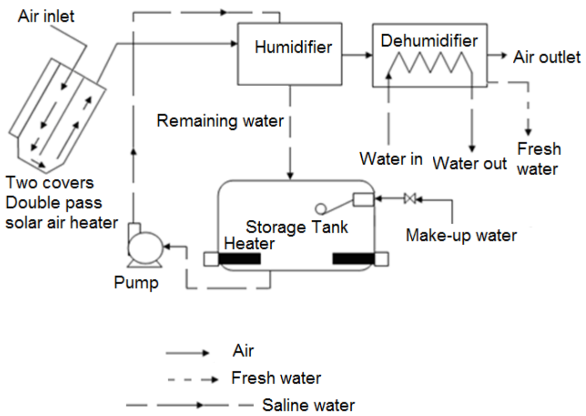
Figrue 13. HDH desalination system with waste heat recovery

It consist of a direct contact humidifier, a dehumidifier, a plate heat exchanger, a fan and a seawater pump with a closed air and an open seawater cycle existing simultaneously in the HDH desalination system. The seawater enters the waste heat recovery exchanger (WHRE) and the waste heat is transferred to the seawater which is then sprayed in the humidifier. With the variation laws of the value for the unit area of water production, it is observed that unit area of water production(UAWP) rises continuously with the increase of the air mass flow rate at all the seawater spraying temperatures. The gained output ratio of the system is shown in Eqn(15).

$$GOR = \frac{m_w \lambda}{m_{exhaust}(h_{exhaust,in} - h_{exhaust,out}) + P_{fan} + P_p} \quad (15)$$

K. A. A. Shabaneh [12]

A. A. Shabaneh theoretically studied the performance of a solar air-heated seawater desalination system using HDH technique based on CWOA cycle under a particular geographical conditions. It consists of a tilted, two pass solar air heater, a humidifier, a dehumidifier in addition to a storage tank. In this system, air alone is heated in the solar air heater as shown in the Figrue 14

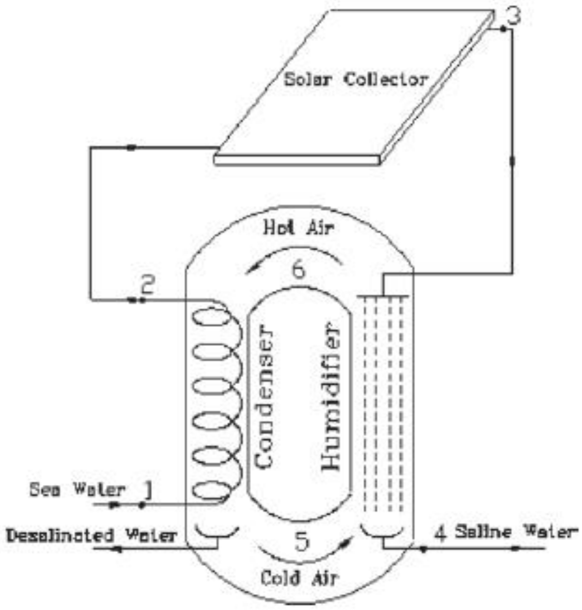


Figrue 14. Schematic of the desalination system

It is observed that the tilted solar heater has higher performance than the horizontal solar heater by 7% and by utilizing a selective surface there is an increase in the desalted water productivity by 39% compared to the other units that do not have a selective surface.

L. Said Al-Hallaj [13]

Said Al-Hallaj reviewed the economics of the solar desalination which has emerged as a promising renewable energy-powered technology for producing fresh water and increasing the overall efficiency of the desalination plant and utilization of solar energy as shown in the Figrue 15.



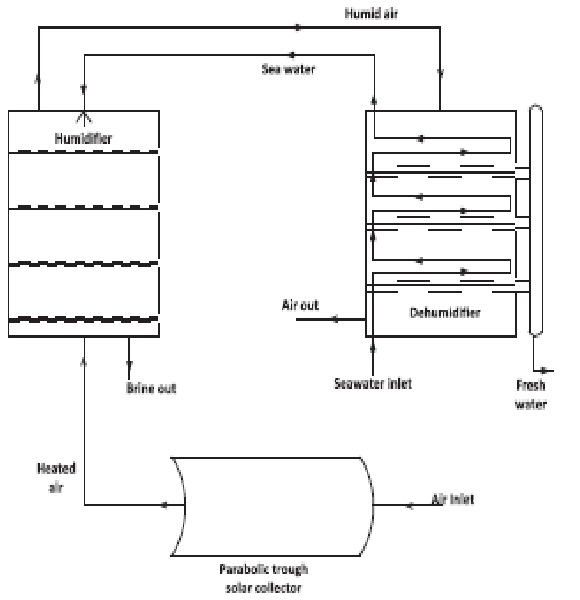
Figrue 15. Sketch of a natural draft air circulation MEH desalination unit

He made a cost analysis for the solar distillation units as per Delyannis and Delyannis. Considering a mean lifetime of 20 years for the plant, the main components of the annual average cost of distilled water C ($m–3) and for a solar powered Multiple effect desalination plant operated by solar collectors or a solar pond, and for feed water of salinity in the range of 5000–35,000 ppm, Goosen et al suggested an equation is used to estimate the cost of distilled water C (in $m–3).

M. Fahad A. Al-Sulaiman [14]

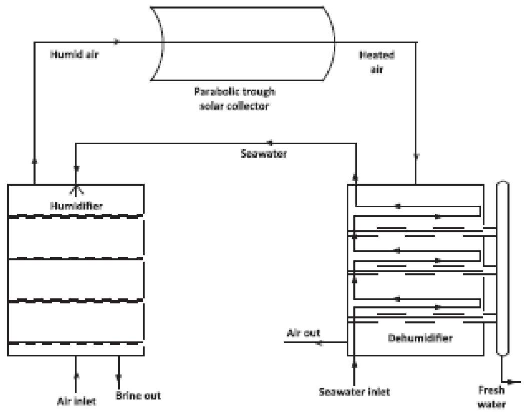
Fahad A. Al-Sulaimanhis conducted a thermodynamic analysis to assess the performance of an HDH system with an integrated parabolic trough solar collector (PTSC) where two different configurations were considered of the HDH system.

In the first configuration, the solar air heater was placed before the humidifier as shown in Figrue 16 with a gained output ratio of 1.5, whereas in the second configuration the solar air heater was placed between the humidifier and the dehumidifier as shown in the Figrue 17 with a gained output ratio of 4.5.



Figrue 16. The first configuration: open-water open-air humidification dehumidification desalination system.

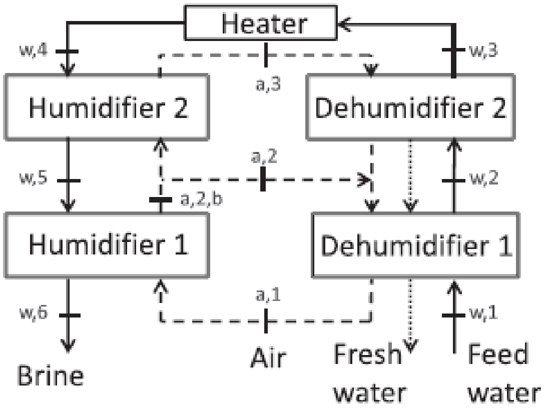
From the thermodynamic analysis made out of the two configurations of the HDH desalination systems integrated with PTSC, the second configuration corresponding to the modified cycle has more GOR



Figrue 17. The second configuration: open-water open-air humidification dehumidification desalination system.

N. Karim M. Chehayeb [15]

Karim M. Chehayeb studied the effect of the mass flow rate ratio on the performance of a fixed-size two-stage humidification dehumidification desalination system as shown in the Figrue 18, and its effect on the entropy generation and the driving forces for heat and mass transfer and a generalized energy effectiveness for heat and mass exchangers. They also implemented an air extraction/injection and simulate a wide range of operating conditions.



Figrue 18. Schematic diagram representing a water-heated, closed-air, open-water HDH system with a single extraction.

The modified heat capacity rate ratio was first defined by Narayan et al. [1] as the ratio of the maximum changes in enthalpy rates of the interacting streams in a heat and mass exchanger as shown in Eqn.16.

$$HCR = \frac{\Delta h_{max,cold}}{\Delta h_{max,hot}} \qquad (16)$$

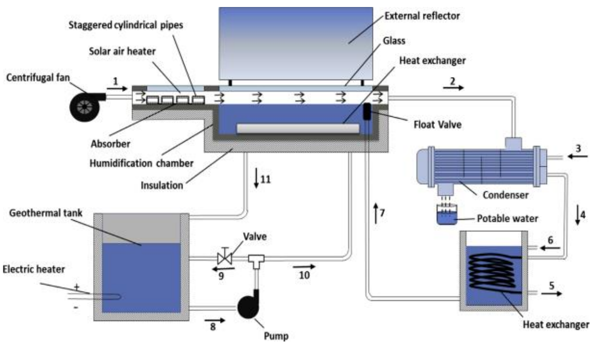
By setting HCR = 1, maximizes energy efficiency and water recovery and minimizes the entropy generation per unit product by minimizing the variances in the driving forces to heat and mass transfer. This results in the best use of the available surface area in the heat and mass exchangers.

O. Nabil A.S. Elminshawy [16]

Nabil A.S. Elminshawy evaluated the technical feasibility and economic feasibility of a humidification-dehumidification (HDH) desalination system using a hybrid solar-geothermal energy source in as shown in the Figrue 19.

Analytical model was also developed to compare the effect of solar energy and combined solar-geothermal energy on accumulated productivity.

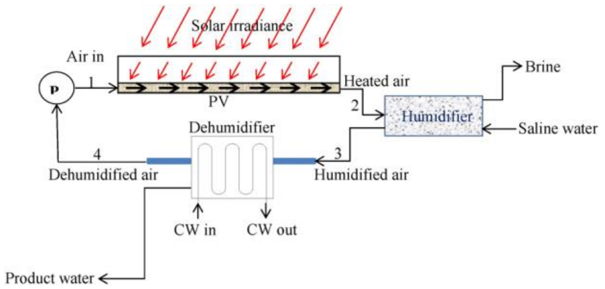
Daytime experimental accumulated productivity up to 104 L/m2 and daily average gained output ratio (GOR) in the range 1.2–1.58 was achieved using the proposed desalination system. Cost of fresh water produced using the presented desalination system is 0.003 USD/L.



Figrue 19. Schematic diagram of experimental test rig.

P. Adewale Giwa [17]

Adewale Giwa investigated the technical feasibility and environmental friendliness of an air-cooled PV system integrated with ambient seawater inflow into a HDH desalination technology with the use of recovered photovoltaic (PV) thermal energy could be viable for the production of small-capacity sustainable water and improvement of PV electric power generation efficiency as shown in the Figure 20.

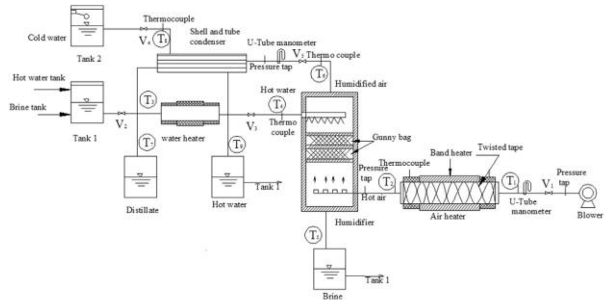


Figrue 20. PV-HDH system.

A technical analysis is made on the photovoltaic humidification-dehumidification seawater desalination process that was carried out through the modeling of the physical and the thermodynamic properties that are found in the recovery of photovoltaic thermal energy. The results showed that the heat recovered from the PV resulted in the production of a daily average of 2.28 L of freshwater per m^2 of PV. The photovoltaic humidification-dehumidification seawater desalination system resulted in 83.6% decrease in environmental effects when compared with photovoltaic-reverse osmosis (PV-RO) system. In conclusion, the integrated PV-HDH desalination technology is promising and expected to play a key role in the field of water desalination.

Q. C. Muthusamy [18]

C. Muthusamy conducted an experimental analysis on the humidification dehumidification (HDH) desalination system as shown in the Figure 20, to accelerate the productivity. In the air heater region of the HDH desalination system, inserts namely (i) twisted tape in short length with tapered form, (ii) cut out conical turbulators integrated with internal fins arranged in convergent and divergent mode and (iii) half perforated circular inserts with an orientation angle of 45°, 90°, and 180° are tried out respectively with pitch ratio (PR) of 3, 4 and 5 to enhance the heat transfer rate in the air heater. Two types of packing materials, such as gunny bag and saw dust, are tested in the humidifier region accommodating the mass transfer rate.



Figrue 20. Schematic view of humidification–dehumidification desalination system.

Also, an attempt has been made to augment the overall heat transfer coefficient in the dehumidifier with spring insert for PR of 3 and 4. An energy and exergy investigation is made which interpreted the quantity of effective utilization of energy with the modified HDH desalination system. The enhanced system produced 45% increase of productivity compared to conventional system of 0.340 kg/h. For the same input power, the modified system enhanced the heat output and productivity equivalent to a power saving of 40% and 13% respectively.

VII. COMPARISON OF PRODUCTIVITY AND OTHER VARIABLES

Various advancements in the field of desalination which are related to the concept of humidification-dehumidification are compared based on their productivity.

Table 1. productivity of various desalination systems [1]

Research name	Max. productivity	$T_{evaperator\ inlet}$	m_{water}	m_{air}
Nawayseh *et al.* [1]	7.8 kg/day	71 - 78 C	Not given	0.005 - 0.03 kg/s
Kabeel A. E. and Emad M. [19]	32.56 kg/day	Not given	4.5 kg/s	0.12:0.32 kg/s
Amer *et al.* [20]	5.8 kg/hr	50:85 C	0.856:2.772 kg/min	Not given
Nafey *et al.* [21]	10.25 kg/day	25.94:36.75 C	0.005:0.045 kg/s	0.0049:0.0294 kg/s
Hermosillo *et al.* [22]	1.45 kg/hr	68.9 - 44.6 C	0.012-0.023 kg/s	0.004 - 0.0043 kg/s
Yamali and Solmus [23]	1.1 kg/h	35.5:50 C	0.085:0.115 kg/s	0.045:0.068 kg/s
Yuan G and Zhang H. [24]	43 kg/day	38:92 C	Not given	Not given
Dai Y.J. and Zhang H.F. [25]	108 kg/h	65:85 C	3780 kg/hr	615.6 kg/hr
Al-Enezi *et al.* [26]	6.4 kg/day	35:45 C	75 kg/h	5:10 nm$_3$/h
Farid M., Al-Hajaj A. [27]	12 l/m$_2$ day	(49:63) C	60:120 kg/hr	40:70 kg/hr
Eslamimanesh and Hatamipour [28]	1.7 m$_3$/day	35:28 C	3.3 kg/s	0.067 kg/s
Farsad S. and Behzadmehr A. [29]	27 kg/hr	15:25 C	0.4:1.4 kg/s	0.4:1.2 kg/s
Farid *et al.* [30]	m$_2$day	60:63 C	Not given	Not given
Fath H.E.S. and Ghazy A. [31]	4.5 kg/m$_2$	40 - 60 C	0.0001:0.0003 kg/s	0.01:1.8 kg/s
Orfi *et al.* [32]	27.9 l/m$_2$.day	Not given	0.08 kg/s	0.05 kg/s
Al Sahali M. and Ettouney H. [33]	100 m$_3$/day	60 - 90 C	0.003 - 0.007 kg/s	0.0013:0.0034 kg/s

VIII. CONCLUSIONS

This review illustrates that majority of the desalination system is based on humidification dehumidification and they are combined with retrofits to increase the productivity of the freshwater and the renewable energy, waste heat recovery methods are implemented to develop an economic model. Also, from this review, no. of topics relating to the desalination systems that have not been addressed by the practical issues include the following

- ✓ Scale formation
- ✓ Deterioration of components
- ✓ Effects of brine to the environment
- ✓ Recycling of brine
- ✓ Very rare form of project
- ✓ Alternative method for desalination systems combined with solar energy duing night time
- ✓ Long-term behaviour of the model
- ✓ Environmental effects

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