A Solar Desalination System Using Humidification-Dehumidification Process- A Review of Recent Research

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Abstract: *Desalination involves any process in which dissolved minerals are removed from saline or brackish water. The paper evaluates the characteristics for several layouts for the humidification dehumidification desalination process. It gives bird-eye view to Humidification-Dehumidification (HDH) process by comparing various authors' works. Necessary schematic figures, graphs between affecting operational and environmental parameters and tables are reviewed. Particular attention was given to all vital components in the system. It is concluded that HDH technology has great promise for decentralized small-scale water production applications, although additional research and development is needed for improving system efficiency and reducing capital cost.*

Keywords: *Humidification-Dehumidification (HDH), Desalination, Double Glazing, Heat Exchanger, Closed Water Open Air System (CWOA), Conventional desalination system, solar air heater.*

I. Introduction

There are two main challenges for the world in the future, shortage of energy and shortage of fresh water, both play a crucial role in the overall economic development of any country [19].Conventional desalination technologies are usually large-scale, technology intensive systems is most suitable for the energy rich and economically advanced regions of the world. They also cause environmental hazards because they are fossil-fuel driven and also because of the problem of brine disposal. In the following sections these conventional desalination technologies are introduced and their drawbacks are discussed .These heaters can amount to over 40% of the total cost of a humidification-dehumidification system and so the development of a cost effective and efficient solar collector is essential to the system's overall feasibility [1].

II. Conventional Desalination Technologies

Desalination processes.
Phase-change processes
1. Multi-stage flash (MSF)
2. Multiple effect distillation (MED)
3. Vapor compression (VC)
Membrane processes
1. Reverse osmosis (RO)
2. Electrodialysis (ED)

Multi Stage Flash (MSF):

Pressurized seawater [2, 8] flows through closed pipes where it exchanges heat, with vapour condensing in the upper sections of the flash chambers. Water is then heated to a certain initial high temperature, using burnt fuel or external steam, and this allows flashing along the lower part of the chambers, from chamber to chamber under reduced pressure conditions. Vapour generated is allowed to flow through a mist eliminator to meet the condensing tubes, where heat is transferred to the heating feed seawater. The condensate drips into collectors and is pumped out as the plant product. Exhausted brine, concentrated in salt, is pumped out and rejected to the sea. Part of the brine is recirculating with the feed in order to increase water recovery.

Multi-effect Distillation (MED):

Basically, the method [2, 17] can use low temperature, low-pressure steam as the main energy source. Steam from burnt coal or fuel can be used, as well as spent steam emerging at the outlet of a steam-operated power station. The primary steam is used to evaporate heated seawater and to generate more steam at a lower pressure, while the primary steam condensate is taken back to the generation chamber, or to the steam generator of the power station. The secondary steam generated goes into a second stage to condense while transferring the latent heat to low temperature seawater, flowing in falling film. The process is repeated as many times as the design permits, between the upper possible temperature and the lower possible cooling temperature, which depends on seawater temperature. The condensate is accumulated stage wise as the product water. A vacuum pump takes the remaining vapour after the last condensation stage, to maintain the gradual pressure gradient inside the vessel.

Vapour Compression (VC):

VC [2] operates mainly at a small scale, on small locations. The main mechanism is similar to MED except that it is based on compression of the vapour generated by evaporating water to a higher pressure, which allows reuse of the vapour for supplying heat for the evaporating process. Compression of the vapour may be carried out by using a mechanical compressor (the most common way), or by mixing with small amounts of high-pressure steam (Thermal Compression). Feed water is preheated against brine and the product leaving the system. Heat transfer usually takes place in the form of a double falling film, which is an effective heat transfer mechanism. The latent heat of the condensing vapour is used to make more vapours on the other side of the heat transfer surface, basically a "heat pump" process, so that the main need for energy is for elevating the pressure to provide the driving force by temperature difference. The process takes place usually from one to three stages, thus the operating temperature may be chosen for the best optimization of the process. No external heat is needed for the mechanical compressor, so basically the technique relies on the electric power supply. Part of the water circulates to increase the water recovery.

Reverse Osmosis (RO):

Osmosis [17] is the movement of a solvent through a semi-permeable membrane into a solution of higher solute concentration. This action tends to equalize the concentrations of solute on the two sides of the membrane. The reverse osmosis process uses pressure as the driving force to overcome the osmotic pressure of the salt solution. A reverse osmosis plant consists of four major systems: Pre-treatment system, High-pressure pumps, Membrane systems and Post-treatment.

Mechanism: Pre-treatment is very important because membrane surfaces need to remain clean. All suspended solids must be removed, microbial bacterial must be removed, and processes include coagulation/flocculation/sedimentation. High-pressure pumps supply pressure from about 150 psi for brackish water to 800-1,000psi for seawater. Membrane materials consist of cellulose acetate or of other composite polymers. Pressure applied to feed water causes clean water to permeate across membrane into central colleting tube. Salts are rejected from the membrane and separation is complete. Post-treatment consists of stabilizing the water by adjusting the pH and disinfection.

Benefits: Continuously operating process, 24 hours a day. New membranes have high rate of water flow per unit area (flux). It is having high overall water recovery rates, salt removal, up to 99.8% low power consumption. Development of energy recovery devices (turbines)is possible. Minimal cleaning is required, longer service.

Limitations: Pesticides, herbicides, and chlorine are molecularly smaller than water and can pass through membrane if not pre-treated correctly. There will be chances of removal of healthy, naturally occurring minerals in water. Wastes a portion of the water that runs through its system. Slower process than other water treatment alternatives.

Electrodialysis:

A voltage is used to move salts through a membrane, leaving fresh water behind. Electro dialysis depends on some general principles; most salts dissolved in water are ionic, meaning they contain a positive (cat-ion) or negative (anion) charge. These ions are attracted to electrodes with an opposite electric charge. Semi-permeable membranes allow selective passage of either an anion or a cat-ion but not both.

Mechanism: Electrodes connected to battery are placed in container of saline water. As electrical current is applied through the solution, the ions ($Na+$, Cl^{-}, $Ca^{2}+$, Carbonate $^{2-}$) migrate to the electrode of opposite charge. Anions (Cl^{-}, Carbonate $^{2-}$) travel opposite of current and pass through an anion semi-permeable membrane. Once through this their path is blocked by a cat-ion semi-permeable membrane and is trapped. The same event happens to the cat-ions, ($Na+$, $Ca^{2}+$) which pass through a cat-ion semi-permeable membrane and are trapped by an anion semi-permeable membrane. The result is two flows of fresh water and three flows of concentrated brine are formed.

Benefits: Automatic operation of the plant, requiring very little maintenance and supervision, except for membrane replacement. It is very effective process for removing and purifying salt concentrate. Applications in many commercial industries, tartaric wine stabilization, de-acidification of fruit juices etc.

Limitations: Pre-treatment is required to prevent materials, which could harm or clog membranes. Works most efficient in low-salinity applications brackish water desalination. Distillation plants produce water that ranges from 1.0 to 50 ppm total dissolved solids (TDS), while reverse osmosis plants produce water that ranges from 10 to 500 ppm TDS. Household RO units typically deliver small amounts (2 to 10 gallons per day) of treated water and waste 3 to 20 times the amount of water treated. RO units use a lot of water. They recover only 5 to 15 % of the water entering the system. The remainder is discharged as wastewater.

Conclusions of Conventional Desalination System:

All configurations i.e. cooling, compression, condensation, or any other form of air drying will result in processing of the large air stream together with the water vapour product. As a result, the process efficiency is drastically reduced. Also, the required size of a condenser or other drying units will be large. Further evaluation of these configurations is necessary to optimize the unit product cost and to minimize the equipment. This would require detailed design of some special equipment such as the desiccant heat exchanger, the absorber, and regeneration units.

III. Review of Humidification-Dehumidification (HDH) Systems

Humidification-dehumidification desalination is a thermal desalination cycle that operates similar to the natural water cycle, where water is evaporated from the oceans by the sun and condenses into fresh water precipitation, which returns to earth and can be used for drinking. This basic principle is behind the operation of a solar still, where the sun evaporates seawater and the vapor condenses on the cooler glazing of the still where it can be recovered for drinking. However, in the process of condensation all the latent heat of evaporation of the water is lost to the environment, leading to poor thermal performance. The HDH cycle improves on this principle by separating the evaporation and condensation processes into different devices thereby recovering the latent heat of evaporation and using it to heat the seawater.

HDH systems are classified under three broad categories. One is based on the form of energy used such as solar, thermal, geothermal, or hybrid systems. This classification brings out the most promising merit of the HDH concept: the promise of water production by use of low-grade energy, especially from renewable resources. The second classification of HDH processes is based on the cycle configuration (Fig. 1). As the name suggests, a closed-water open air (CWOA) cycle is one in which the air is heated, humidified and partially dehumidified and let out in an open cycle as opposed to a closed-air cycle wherein the air is circulated in a closed loop between the humidifier and the dehumidifier. The air in these systems can be circulated by either natural convection or mechanical blowers. The third classification of the HDH systems is based on the type of heating used: water- or air-heating systems. The performance of the system depends greatly on whether the air or water is heated.

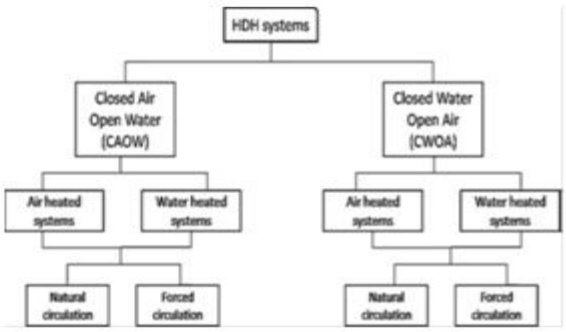

Figure.1 Classification of typical HDH processes (based on cycle configuration).

Y.J. Dai et al [3] has performed on water heated closed water open air (CWOA) system havingunit features like honeycomb wall humidifier, forced air circulation; the condenser is a fin-tube type. Main observations are large pressure losses can be avoided, condensation heat is recovered efficiently, other low-grade heat resources such as waste heat, gas/oil/coal burning, etc, can also be efficiently utilized. Guofeng Yuan et.al [4] work on water heated CWOA system having unit features of honeycomb paper used in humidifier, forced convention for the air circulation, condenser is fin tube type. Main observations are performance strongly dependent on temperature of inlet salt water to the humidifier, the mass flow rate of salt water, and the mass flow rate of the process air, the authors report that there is an optimal air velocity for a given top temperature of water. CemilYamali et al. [5] has performed on water heated CWOA having a single stage double-pass flat-plate solar collector heats the water, a pad humidifier is used and the dehumidifier used is a finned tube heat exchanger also a tubular solar water heater was used for some cases. It was observed that the plant produced 4 kg/day maximum, increase in air flow rate had no effect on performance, and an increase in mass flow rate of water increased the productivity. nil Kr Tiwari [6] was worked by using double-pass flat plate solar air heater with two glass covers, mathematical modeling & observed that the productivity of the proposed system increases up to 10% & air mass flow rate should have optimum value. Orfi et al [7] used combined air heated (open or closed one) and water heated solar heater, evaporator, the condenser contains two rows of long cylinders made of copper in which the feed water flows. Longitudinal fins are soldered to outer cylinder. Both theoretical & experimental study was made on the system. The theoretical results show that there exists an optimum mass flow rate corresponding to a maximum fresh water product.

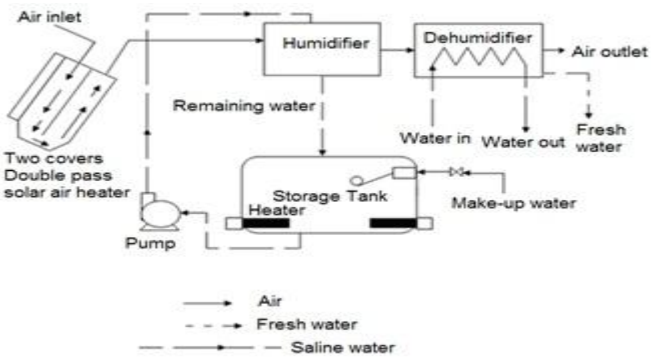

Figure.2 Schematic of humidification-dehumidification desalination process

Procedure starting from air intake into solar air heater to final product fresh water is described by schematic of desalination system as shown in Figure 2. It essentially consists of a tilted, two-pass solar air heater with two glass covers, a humidifier, a dehumidifier and a storage tank. In this system, air alone is heated in a solar air heater. The system is composed of three main fluid-circulation lines identified in Fig. 2 as saline water, air/vapor, and freshwater. The saline water which is circulated in the humidifier is in contact with a continuous flow of ambient air already heated in a solar collector. Then, air is cooled and humidified as it passes upward through the falling saline water in the humidifier. The humidified air is passed through a dehumidifier where it is cooled using cooling water stream in the condenser. The partially dehumidified air leaves the unit, while the distillate (condensate) is collected as fresh water. The saline water leaving the humidifier is collected in a storage tank and recirculates to the humidifier. In this study, air is heated by using a tilted two-pass solar air heater whereas water is only heated by bringing it to contact with air in the humidifier and a inside the storage tank so that a constant temperature in the storage tank is accordingly maintained. The effect of the air temperature on the system productivity is examined at different values of air mass flow rates.Nafey et al. [9] uses system which is unique in that it uses a dual heating scheme with separate heaters for both air and water. Humidifier is a packed bed type with canvas as the packing material. Air cooled dehumidifier is used and hence there is no latent heat recovery in this system. The authors reported a maximum production of 1.2 L/h and about 9 L/day. Higher air mass flow gave less productivity because increasing air flow reduced the inlet temperature to humidifier.Chafik et al [12] work with solar collectors (four-fold-web-plate, or FFWP, design) of 2.08 m^2area heat air to 50^0 –80^0C, multi-stage system, pad humidifier with corrugated cellulose material, 3 separate heat recovery stages & forced circulation of air. The solar air heaters constitute 40% of the total cost. Also he observed that the system can be further improved by minimizing the pressure drop through the evaporator and the dehumidifiers.

IV. Review of Solar Air Heater

Various types of solar air heaters according to construction & there features are discussed one by one. Air flow over the absorber plate where the absorber decreases losses from the top of the absorber plate and eliminates conduction resistance through the plate. Roughened absorber plate used to improves convection heat transfer into the air. A rough configuration also increases pressure drop, but only marginally as compared with a smooth plate. Multiple passes of air through the collector improves heat gain by increasing contact with the absorber and makes the absorber run cooler, decreasing lose. Multiple glazing layers, it reduces heat loss by infrared radiation and trap an insulating air layer between the glazing. Glass and metal construction, it provides better heat transfer characteristics and better durability. All the best performing collectors used glass and metal construction, as polymer alternatives, especially for glazing's, suffer from low durability, although initially providing optical properties comparable to glass. Packing materials in the air stream improve heat transfer by mixing the air and providing more surface area to absorb radiation. Packing also provides sensible heat storage but comes at the cost of high pressure drop.

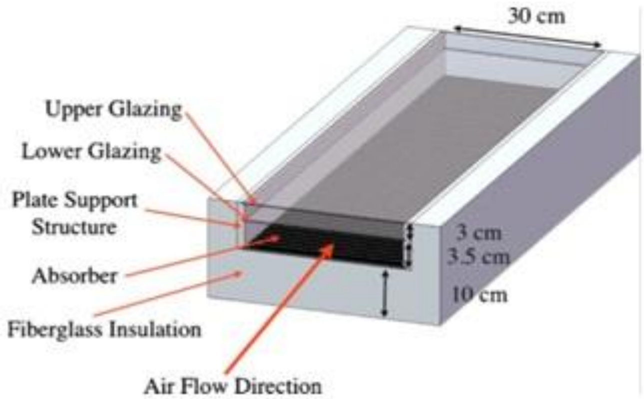

Figure.3 Double pass solar air heater

Guofeng Yuan [4] works on the72 pieces of solar air heaters with a total surface area of approximately 100 m^2. These collectors use evacuated tubes with inner pipes, which could provide higher air temperature than panel solar collectors. 72 pieces is divided into 2 subgroups containing 36 pieces/group & they are connected in parallel. Then each group is divided again into 3 sub-groups (12 pieces/sub-group), with pieces in every single sub-group connected in parallel, and sub-groups connected in parallel as to each other in order to ensure the uniformity of air distribution and reduce air flow rate in the air Trunk. Author [5, 6&11] used double-pass flat plate solar air heater (100*50*10 cm^3) as shown in Fig. 3. It consists of two glass covers having a thickness of 3 mm matt black painted 1 mm thick copper absorber plate. The container of the solar air heater that was made of iron sheets of 2 mm thickness was fabricated by welding. The solar air heater was positioned at a tilt angle of 30° facing south Productivity increases about 15% by double-pass solar air heater. A tubeless flat plate solar collector with a single glass cover is used for air heating. The Heater effective area is 0.5 m*1 m, and the absorber plate is made of copper with a thickness of 0.5 mm. The air gap between the absorber and the glass cover is 0.01 m [7-10] which could provide higher air temperature than panel solar collectors. Heat gain by air is denoted by process 3-1 in psychometric chart (Fig .8).

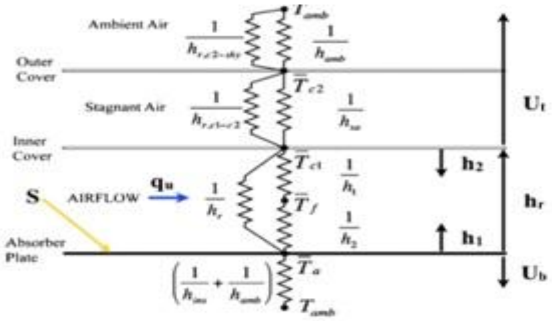

Figure.4 Heat transfer resistances with lumped parameters

When considering the design of a solar air heater Edwerd K. Summers [1] suggest two design parameters that vary based on collector design. One is the overall heat loss coefficient, U_L, which is related to the heat-transfer coefficients in the collector, and which needs to be minimized. This is given by Eq. (1) for a flat-plate air heater with air flowing over the absorber.

$U_L = [(U_t + U_b) (h_1h_2 + h_1h_r + h_2h_r) + U_bU_t (h_1 + h_2)]/ [h_1h_r + h_2U_t + h_2h_r + h_1h_2]$ Eq. 1

The second parameter is F_0, which is the useful heat gain coefficient or the ratio of actual energy gain to the energy gain that would result if the absorber plate was at the local fluid temperature. This ratio needs to be maximized to enhance efficiency. Eq. (2) gives $F_0$for the same flat-plate air heater.

$F_0 = [h_rh_1 + h_2U_t + h_2h_r + h_1h_2] / [(U_t + h_r+ h_1) (U_b + h_r + h_2) – h_r^2]$ Eq. 2

To see how each parameter fits into the overall useful heat gain Eq. (3), or the overall collector governing equation, is also given. $q_u = (S – U_L(T_f –T_a))$ Eq. 3

S is the total energy that is absorbed by the absorber. U_b and U_t are the overall heat-transfer coefficients from the top and bottom of the air stream to the outside, respectively, h1 is the heat-transfer coefficient from the glazing plate to the air stream, h_2 is the heat transfer coefficient from the absorber to the air stream, and h_r is the linearised radiation heat-transfer coefficient from the absorber to the glazing.

Gained-Output-Ratio (GOR): the ratio of the latent heat of evaporation of the distillate produced to the total heat input absorbed by the solar collector(s). This parameter is, essentially, the efficiency of water production and an index of the amount of the heat recovery effected in the system. This parameter does not account for the solar collector efficiency as it just takes into account the heat obtained in the solar collector. For the HDH systems to have thermal performance comparable to MSF or MED, a GOR of at least 8 (corresponding to energy consumption rates of 300 kJ/kg) should be achieved.

Solar air heater efficiency: It is defined by $\eta= m c_p (T_{out} - T_{in})/ I_T$, Eq. 4

Where m is mass flow rate of air through the collector in kg/s; C_p is specific heat capacity of air at constant pressure in J/kg K; T_{out} outlet temperature of air, K; T_{in}-inlet temperature of air, K; I_T solar irradiation, W/m^2.Efficiency of different type of solar collector is provided in figure5.

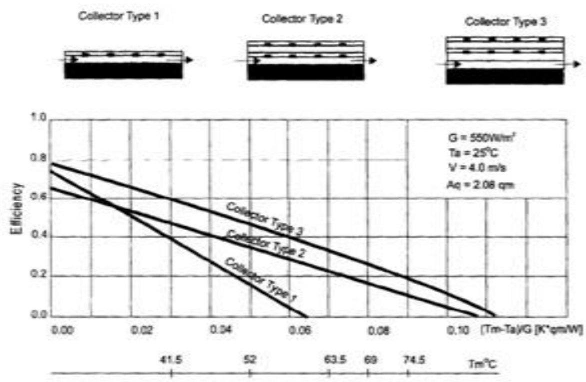

Figure.5 Efficiency of different collector types [12]. Tm, mean temperature of air in the collector, ‘C; Ta, ambient temperature, “C; G solar irradiation, W/m2; Aq, collector area, m^2; C: air velocity, m/s.

V. Review of Humidifier

Kreith [24] used spray tower which is cylindrical vessel in construction water is sprayed at the top of the vessel and air stream flowing upward (Fig.6). The diameter-to-length ratio is a very important parameter in spray tower design. Design of spray towers requires knowledge of heat and mass transfer coefficients as well as the contact surface area of the water droplets. Minimal pressure drop on the gas side considerable pressure drop on the water side due to the spray nozzles High capacity but low efficiency, the low efficiency is as a result of the low water hold-up due to the loose packing flow. Many empirical correlations and design procedures are used by various authors.

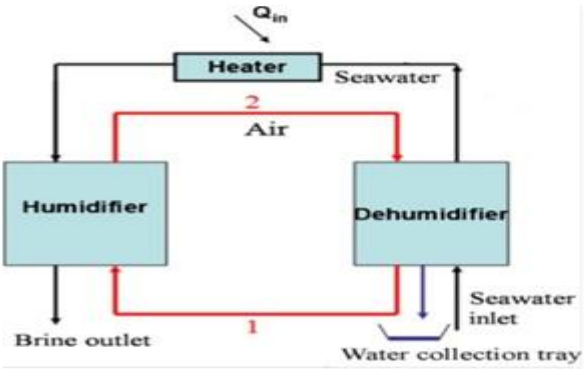

Figure.6 A typical water-heated CAOW HDH process

The most common way to express performance of the humidifier is its efficiency given by eq.5 [5] $\eta = (\omega_{out} - \omega_{in})/(\omega_{out,sat} - \omega_{in})$, where ω_{out} is outlet humidity ratio; ω_{in} is inlet humidity ratio; and $\omega_{out,sat}$ is outlet humidity ratio at saturation. During humidification specific humidity increases with small drop in temperature as given by process 1-2 in a psychometric chart (Fig. 8). El-Agouz and Abugderah [25] studied the single Bubble column exactly opposite in principle to the spray tower is the bubble column. A vessel is filled with water and air bubbles are ejected from several orifices located at the bottom of the vessel. The diffusion of water into the air bubbles depends on many parameters such as bubble diameter, bubble velocity, gas hold-up (the ratio of air bubbles-to-water volume), water and air temperatures as well as the heat and mass transfer coefficients geometrical factors such as the orifice diameter, number of orifices, water head height and column diameter influence the performance. Muller-Holst et al. [26] was worked with Wetted-wall towers in which Pipes are arranged in vertical manner water is loaded into the top of the tower. A weir distributes the flow of water around the inner perimeter of the tube that wets the inner surface of the tube down its length. Such devices have been used for theoretical studies of mass transfer. A thin film of water is formed running downward inside a vertical pipe, with air flowing either co-currently or counter currently. J. Orfi [7] in his experiment use evaporators to increase saturation point of incoming hot air. Evaporators is horizontal and has a rectangular cross section is constructed with wood. The fiber glass is used for insulation. Five parallel plates made with wood and covered with textile (cotton) are fixed in the evaporator. Tubes are placed on the vertical plates. The feed water and the air are counter current. Evaporators provide better heat and mass exchange. The horizontal surface of the evaporator is covered by the hot water. The vertical plates are wetted by capillarity and finally the water is sprayed by means of tubes with small holes set in them.

Table I: Packing material used in packed bed towers for humidification in HDH systems.

Author	Packing material
Al-Hallaj et al. [20]	Wooden surface
Nafey et al. [9]	Canvas
Yamali et al. [5]	Plastic packing
EfatChafik [12]	Corrugated cellulose material
Dai and Zhang [3,4]	Honeycomb paper

VI. Review of Dehumidifier

Dehumidifiers is heat exchanger in which heat exchange is takes places between two fluids i.e. hot and cold that are at different temperatures. The heat exchange in the heat exchanger may be in the form of latent heat or sensible heat or combination of both. Solid wall may or may not separate two fluids.
There are various types of heat exchangers (dehumidifier) which may be classified on the basis of the following

Nature of heat exchange process:

Direct contact (open): Heat exchange takes place through direct mixing of hot and cold fluids. Examples are cooling towers, jet condensers and direct contact feed heaters.

Indirect contact (surface): Regenerators- In this hot and cold fluids are flow alternately through same space alternately with no or little mixing between the streams. Examples are the regenerators are used in most of the gas to gas heat exchangers such as internal combustion engine and gas turbines. Other applications include open hearth and glass melting furnaces and air heaters of blast furnaces. Recuperators- This is the most common type of heat exchanger in which two fluids are separated by surface between them. Examples are oil coolers, intercoolers, economiser, super heaters, condensers, radiators and evaporator.

Relative Directions of Fluid Motions:

Parallel flow-In this hot and cold fluids flow in the same directions. Examples are water heaters, oil coolers etc.
Counter flow-This is the most favourable device in which hot and cold fluid flows in opposite directions.
Cross flow-Two fluids are flow in normal to each other for example automobile radiators.

Design and Construction Features:
It includes concentric tube**,** shell and tubes; multipleshellsand tube passes and compact heat exchanger.

Physical State of the Fluids:
In this category Condensers and Evaporators are present according to state of fluid.

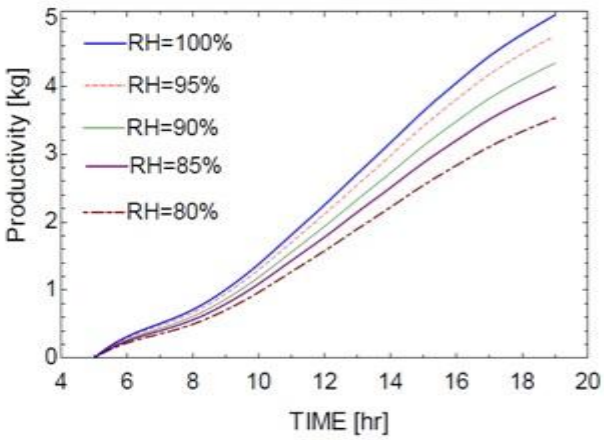

Figure.7 The effect of the relative humidity on the system productivity

The process air passes through the condenser cooled by cold seawater where water vapor condenses and turns into fresh water.The condenser of a fin-tube type one of cross sectional area 1.5*1.5 m was used by Y.J. Dia [3]. Cold seawater flows in the tube channel and fresh water is produced on condensation surface in the condenser at the same time. The effect of the relative humidity on the system productivity is given in Fig. 7. In similar study G. Yuan [4] is used two parallel fin tube heat exchanger one above other to strengthen the cooling capacity. Special feature is that humidifier and dehumidifier is composed as single equipment having no physical isolation between them. J. Orfi [7] used. The condenser consists of a chamber with a rectangular cross section. It contains two rows of long cylinders made of copper in which the feed water flows. On outer surface of it saturated water vapour flow along length, during the process (process 2-3 in Fig. 8) fresh water is recovered and thereby drop in temperature and specific humidity of air. Longitudinal fins were soldered to the outer surface of the cylinders. The condenser is characterized by an exchange surface, 1.5 m ^{2}and 28 m total length. K. Bouroni [8] used horizontal tube bundle through which the brine coolant passes in counter-current flow to the fresh water stream surrounding the tube bundle is the most used configuration. Cemil Yamali [5] worked with three-air cooler heat exchangers manufactured with copper tubes and corrugated aluminum fins were used as a dehumidifier. They were connected to each other with copper tubes in series (exit of one cooler was connected to the inlet of the other cooler). The surface area of each condenser is 3.5 m^2 (i.e., the total surface area of the dehumidifier is 10.5 m^2). In order to prevent air leakage and heat gain, dehumidifier heat exchanger was placed on an insulated metal box. It was constructed of 2 mm thick galvanized steel by welding. Its dimensions are 40 cm × 47 cm × 34 cm.

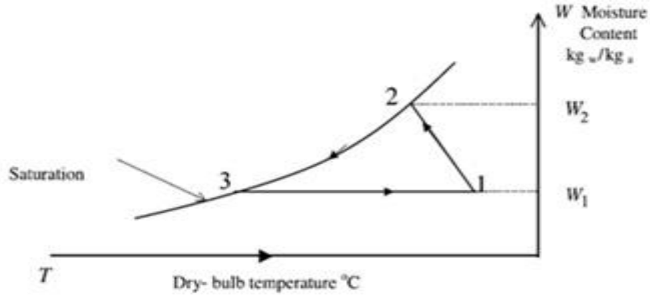

Figure.8 A typical air-heated HDH cycle on psychometric chart

Chafik [12] used seawater as a coolant wherein the water is heated by the humid air before it is pumped to the humidifiers. Three heat exchangers were used in three different condensation stages. A additional heat exchanger is added at the intake of sea water (low temperature level) for further dehumidification of air. The heat exchangers (dehumidifiers) are finned-tube type air coolers. They developed a theoretical model. The standard method as developed by McQuiston [14] considers finned-tube multi-row multi-column compact heat exchangers and predicts heat and mass transfer rates using Colburn j-factors along with flow rate, dry- and wet-bulb temperatures, fin spacing and other dimensions. The air side heat-transfer coefficient is based on log-mean temperature difference for the dry surface whereas under the condensing conditions, the moist air enthalpy difference is used as a driving potential.

VII. Conclusions

The Humidification-Dehumidification (HDH) process presents a very interesting solution for small units (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 an attractive cost (cogeneration, solar energy, geothermal energy, etc.)[8]. From the present review it is found that among all HDH systems, the multi-effect CAOW water-heated system is the most energy efficient[14]. A collector with a double glazing, a highly roughened absorber, and a carbon black coated absorber, results in a collector efficiency of 58% at a normalized gain of 0.06 K m^2 /W [1]. It is necessary to obtain the best design and operating conditions that give the minimum product cost.

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