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Water Evaporating Using Humidification and Dehumidification Process for Desalination of Sea Water : A Review

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ABSTRACT

Lack of clean water and a lack of functional energy are two major issues that will hinder global development in the future. These issues also have a significant impact on the general social and economic transformation of any nation. Large-scale, technologically complex systems are typical of conventional desalination methods, making them best suited for the world's most energy-rich and developed locations. Traditional desalination plants run on fossil fuels and have brine disposal issues, they also pose a risk to the environment. In this review paper, the work on design of solar energy powered humidification-dehumidification based desalination system creation has been discussed. The design of an affordable and effective solar collector is crucial to the system's operation because these heaters can account for more than 40% of the overall cost of a humidification-dehumidification system.

Keywords: Humidification, Dehumidification, Desalination, Solar energy.

1. Introduction: Need and Relevance

A clean water supply has become essential to life due to the swift rise of the industrial and agricultural sectors as well as the population. Many reservoirs have dangerously low fresh water levels. The remaining freshwater supplies are contaminated by waste water from industrial facilities, plants, and big city sewage. Glaciers and ice caps make up 2% of the planet's water, whereas fresh water makes up 0.5%. whereas 97% of water is found in the sea. Accessible potable water has turned into a scarce resource. Large seawater is available in India. Desalination is becoming a crucial method for producing fresh water as a result. The Humidification-Dehumidification process using solar energy for water desalination has a number of benefits, including decentralized application, easy installation, low operation costs, flexibility in capacity, and simplicity. In recent years solar energy has garnered the most attention out of all the renewable energy sources since it is abundant, free, clean, and emits no noise or environmental pollutants.

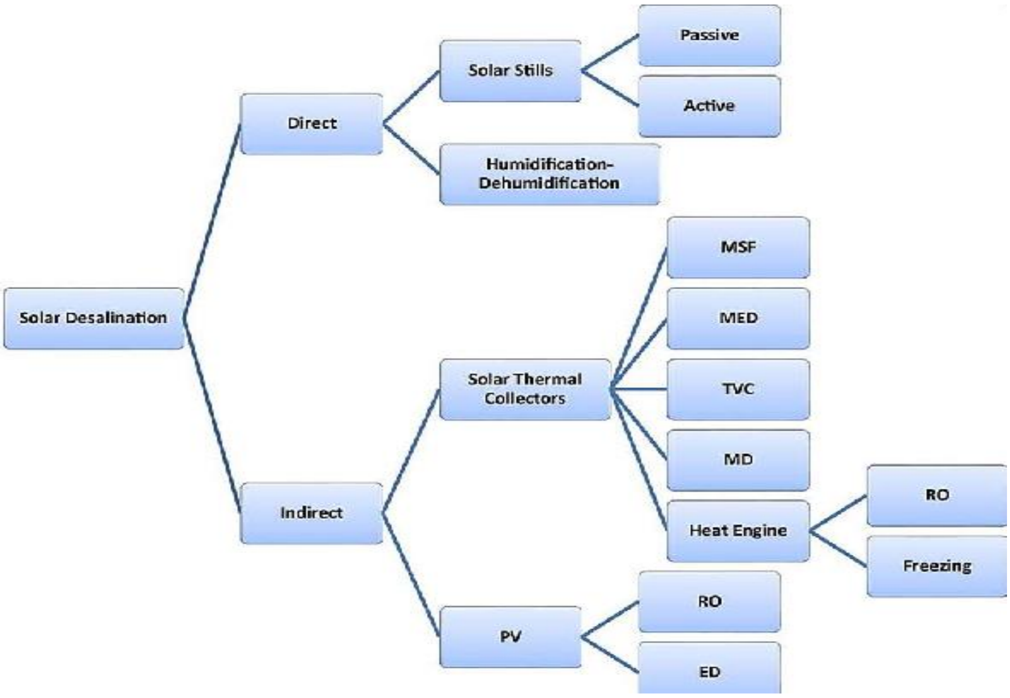

Fig.1.1 Classification of Solar Desalination

Depending on the location, the daily average solar energy incident over India ranges from 4 to 7 kWh/m^2 with 1500–2000 sunshine hours annually. In Gujarat, the daily total solar insolation is greater than 5.25 kwh/m^2. This review paper focuses on the exploring design of solar collectors with the humidification method of evaporation using solar energy.

2. LITERATURE REVIEW

2.1 Humidification-dehumidification (HDH) desalination technology:

Through the rain cycle, nature uses solar energy to desalinate ocean water (Fig. 2.1). Seawater heats up from solar radiation and becomes humid during the rain cycle, acting as a carrier gas in the atmosphere. After that, clouds are formed when the humid air rises. The clouds eventually "dehumidify" and begin to rain. The humidification–dehumidification desalination cycle (HDH cycle) is the artificial version of this cycle.

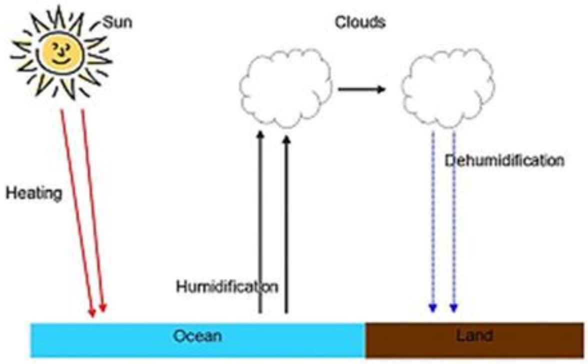

Fig 2.1 Rain Cycle

2.2 Principle of The Humidification–Dehumidification Process:

Bourouni has examined the fundamentals of how the HD process operates. Air has a temperature-dependent vapor carrying capacity. A certain amount of vapor is extracted by flowing air when it comes into contact with salt water, which causes cooling. Conversely, recovered distilled water can be achieved by allowing the humid air to come into contact with a cooled surface, which leads to some of the vapor in the air condensing. The latent heat of condensation usually causes the condensation to happen in another exchanger, preheating the salt water. For this reason, an external heat contribution is required to offset the heat loss that is sensitive. When there is a decentralized demand for water, the HD technique works particularly well for desalinating seawater. Thermodynamic process involved in HD Technique can be represented on psychrometric chart.

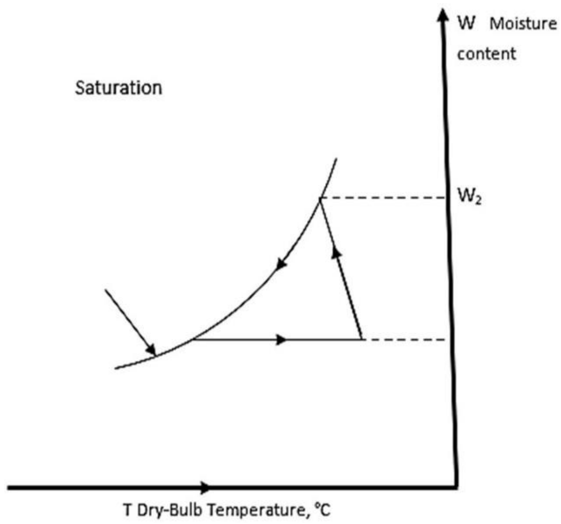

Fig 2.2 Thermodynamic Process Involved In HD Technique (Psychrometric chart)

2.3 Classification of typical HDH processes (based on cycle configuration)

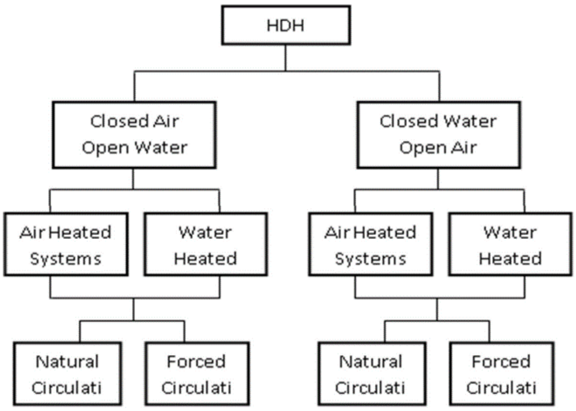

Fig 2.3 Classification of typical HDH processes

2.3.1 Closed-air open-water (CAOW) water-heated systems:

Fig. 2.4 depicts a typical CAOW system. Hot water is used to irrigate the humidifier, and the energy from the hot water stream is used to heat and humidify the air stream. Lines 1-2 on the psychometric chart (Fig.2.4) represent this process. After that, the dehumidifier receives the humidified air, which is then cooled with seawater acting as the coolant in a small heat exchanger. Before the seawater irrigates the humidifier, it is first preheated and then heated further in a solar collector (Q in Fig. 2.4 indicates the heat absorbed in the solar collector by the seawater as used in the calculation of GOR). The humidifier receives a recirculated supply of the dehumidified air stream from the dehumidifier. Line 2–1 on the psychometric chart represents this process.

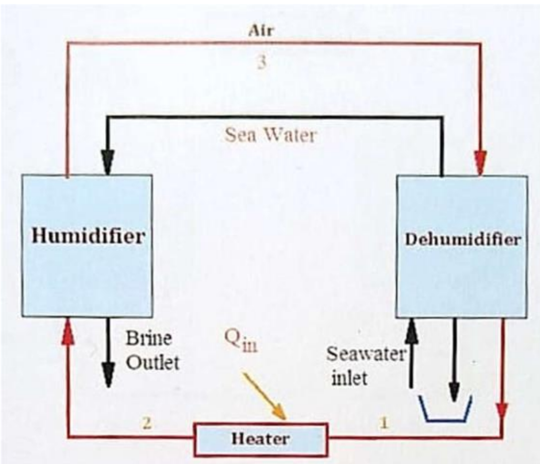

Fig 2.4 Closed-air open-water (CAOW) water-heated systems

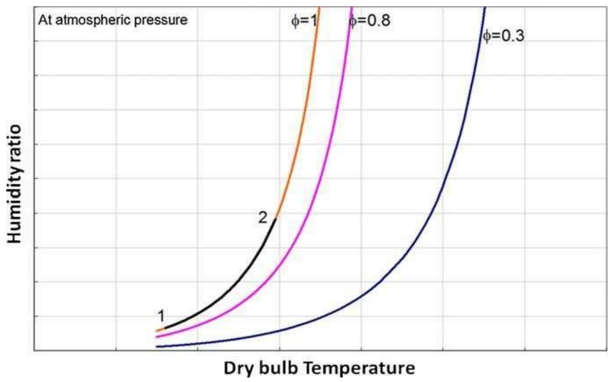

Fig 2.5 Closed-air open-water (CAOW) water-heated system on psychometric chart

2.3.2 Closed-water open-air (CWOA) water-heated systems:

In Fig. 2.6, a typical CWOA system is displayed. Using hot water from the solar collector, the humidifier warms and humidifies the air in this system. The humidifier's outlet water is then used to dehumidify the air. The water functions in a closed loop when it enters the solar collector after first being preheated in the dehumidifier. The dried air is let back into the surrounding atmosphere. Lines 1-2 of the psychometric chart (Fig. 2.6) depict the humidification process. When air enters the humidifier at room temperature, it is saturated up to point 2 and then moves along lines 2-3 in the dehumidifier. The saturation line is where the air is dehumidified.

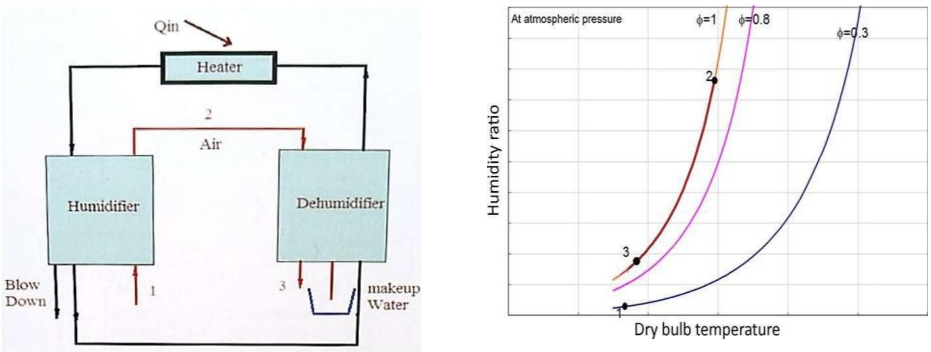

Fig 2.7 Closed-water open-air (CWOA) water-heated system

2.3.3 Closed-air open-water (CAOW) air-heated systems

The air-heated system (Table 2.3) is another class of HDH systems that has garnered a lot of interest. Single and multi-stage systems are the two types of these systems. A single stage system's schematic diagram is shown in Fig. 2.8. After being heated to between 80 and 90 degrees Celsius in a solar collector, the air is routed to a humidifier. The psychometric chart's constant humidity lines 1-2 (Fig. 2.8) represent this heating process. The air is saturated and cooled in the humidifier. Lines 2-3 serve as a representation of this procedure. Next, as shown on the saturation line in steps 3–1, it is cooled and dehumidified. The cycle's primary drawback is the extremely low (<6% by weight) absolute humidity of air that can be attained at these temperatures. This reduces the cycle's water productivity.

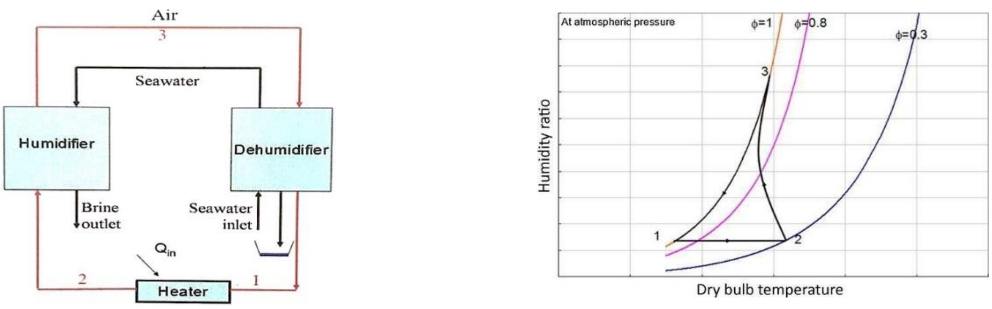

Fig 2.8 Closed-air open-water (CAOW) air- heated systems

2.3.4 Air-heated CWOA HDH process:

The air after getting heated in the solar collector (line 1–2) Air humidified in the evaporator (line 2– 3) It is dehumanized in the condenser. The rapid advancement of the reverse osmosis process (RO) has a significant negative impact on desalination research and the development of new technologies for small capacity plants. The use of large-scale, dependable multi-stage flashing desalination plants (MSF) is another crucial component. Additionally, even in rural and sparsely populated areas, the use of water distribution networks is widespread. Due to these challenges, the development and application of new technologies are extremely difficult. Another significant factor is the continued use of large-scale, dependable multi-stage flashing desalination plants (MSF). Additionally, even in rural and sparsely populated areas, the use of water distribution networks is widespread. Because of the lack of field experience and the difficulties in applying and accepting new technologies, this makes the development and use of new technologies extremely challenging. Despite this, MSF plants require a significant amount of capital, especially when combined with an extensive water distribution system. Additionally, the preparation of modules and membrane synthesis in the RO process demand advanced technological capabilities. Furthermore, feed pretreatment is typically required and intensive for the RO process.

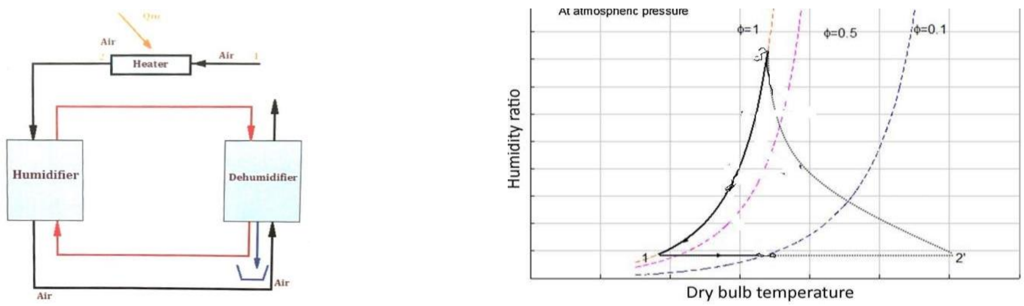

Fig 2.11 Air-heated CWOA HDH process on psychometric chart

2.4 Development and use of New Technologies:

It is very desirable for plants with small capacities. However, pilot scale units and early prototypes might not be the best option in the end. Nonetheless, these endeavors could be beneficial in the long run, when the highly anticipated desalination process which is dependable, affordable, and efficient might be partially or entirely developed. These methods include using different kinds of heat pumps in conjunction with more energy-efficient heating and cooling systems, utilizing solar power or other renewable energy sources, using non-traditional building materials like plastic, and utilizing more energy-efficient evaporation/condensation units.

The conceptual design of several schemes for water desalination using the humidification/dehumidification system (HDH) is the main focus of this study. Researchers highly value this configuration due to its low technological requirements. Both remote areas with sparse populations and industrial sites may find this design appropriate. A thorough analysis of earlier research in the field reveals that a significant portion of these studies are devoted to assessing the performance of the HDH system in conjunction with solar energy. Additionally, testing this configuration's multiple effect form is intended to improve system performance.

Vlachogiannis et al. present a novel concept that involves mechanical compression followed by air humidification. According to reports, this configuration has a very high specific power consumption that is nearly 100 times higher. The traditional HDH method consists of three primary components. These are the feed seawater heater, the condenser, which cools the humidified air to condense the product water, and the humidifier, which raises the humidity of the intake air to saturation levels. It should be mentioned that the dehumidification unit preheats the seawater intake. The feed heater continues to heat the seawater feed. In order to attain the intended design conditions, this is required.

This is produced using an external heat source, such as a diesel engine, solar collector, steam boiler, or other low-grade energy source. The humidifier, condenser, and heater designs are all analyzed in the conventional HDH. When modeling these systems, steady state operation and minimal environmental losses are assumed. It is also believed that the air stream is saturated as it exits the condenser and humidifier. The design equation for the humidifier volume and the overall energy balance are included in the humidifier model. To find the humidifier volume, a straightforward model is employed.

A study on the development of the HD technique for water desalination in India's arid zones was reported by Garg et al. [28] in 1968. Depending on variations in solar radiation intensity, a solar still developed in the first stage at the Central Salt and Marine Chemicals Research Institute, Gujarat, India, produced 2.94–3.91 L/m2 of still area. The solar-powered HD technique addressed some of the shortcomings of the solar still technique. Early on in the HD technique's development, an experimental unit with a capacity of 3 L/d (24 hours) was produced. There was less than 50 parts per million of salt in the distillate that was taken out of the unit. The brine was heated with an electric heater. Based on experimental runs, a liquid-gas ratio (L/G) of about 3 was found to be appropriate for lower temperatures, about 550C. At a brine temperature of 60°C, that unit produced

3.4 L/d.

A techno-economic analysis of an air HD desalination process was carried out by Khedr [2]. The findings demonstrated that condensation recovers 76% of the energy used by the humidifier. Their cost analyses demonstrated that the HD process can operate systems with an output as low as 10 m^3/d and has a great deal of potential as a substitute for small-capacity desalination plants. Raising the water temperature at the humidifier's inlet on the MEH unit resulted in an increase in desalination productivity. Air circulation was also discovered to be crucial for improving system performance. A test rig for a MEH solar desalination plant based on the humidification principle was built by Madani and Zaki [1]. On a normal summer day at noon, the unit produced 0.63–l.25 L/m^2 h of fresh water (2.5–5 L/m^2 d for a 4 h/d peak time operation), which is comparable to some effective single-basin stills.

2.5 Humidifier designs

A variety of equipment, such as spray towers, bubble columns, wet wall towers, and packed bed towers, are used to humidify air [6]. Every one of these devices operates on the same principle. Water diffuses into air and increases air humidity when it comes into contact with air that is not saturated with water vapor. The concentration differential between the water vapor in the air and the water-air interface acts as the driving force behind this diffusion process. The partial pressure of water vapor in the air and the vapour pressure at the gas-liquid interface determine this concentration difference. Any of the above-mentioned devices can be used as a humidifier in the HDH system. For example, a spray tower is essentially a cylindrical vessel with a continuous air stream flowing upward and water sprayed at the top of the vessel, which moves downward by gravity and disperses into droplets. These towers have a small gas side pressure drop and a straightforward design. Nonetheless, the spray nozzles cause a significant pressure drop on the water side. Furthermore, because of the air leaving the tower's propensity to entrain water, mist eliminators are always required. This device's large capacity and low efficiency are well known.

The low water holdup resulting from the loose packing flow is the cause of the low efficiency [7]. One crucial factor in the design of a spray tower is the diameter-to-length ratio. The spray and air will be well combined for a large ratio. A small ratio of diameter to length will allow the spray to reach the tower walls quickly, forming a film that will render it useless as a spray. The contact surface area of the water droplets as well as the mass transfer and heat coefficients must be understood in order to design the 21 spray towers.

Kreith and Boehm [8] provide numerous design procedures and empirical correlations. The humidifier in Younis et al.'s [9] and Ben-Amara et al.'s [10] HDH systems was a spray tower. The spray tower humidifier was tested by Ben-Amara et al. [10] by changing the mass flow rate ratio of

water to dry air while maintaining constant absolute humidity and inlet water temperature. The temperature of the water spray was 60°C, while the inlet air was 80°C. They discovered that the absolute outlet humidity rose as the amount of water sprayed increased.

Nevertheless, when the amount of water was increased further, the air cooled and some of the water vapor in the air condensed. Despite the fact that the outlet air is constantly saturated, this indicates a drop in absolute humidity. Thus, there is an ideal mass flow ratio that yields the highest air humidity for air-heated HDH cycles. This information encourages the use of humidifier and multi-stage air heater combinations to boost the output of fresh water. The bubble column is conceptually exactly opposite to the spray tower. A vessel filled with water is used in the bubble column, and air bubbles are released from a number of orifices at the bottom of the vessel. Humidified air is released from the outlet as a result of water diffusing into the air bubbles.

Although the design of these columns is straightforward, the diffusion of water into the air bubbles is dependent on a number of factors, including the air and water temperatures, the heat and mass transfer coefficients, bubble diameter, bubble velocity, and gas hold-up, which is the ratio of air bubbles to water volume. Bubble columns have not yet been utilized as humidifiers in HDH desalination systems.

On the other hand, El-Agouzand Abugderah [11] used air bubbles traveling through seawater to experimentally study the performance of a single stage bubble 22 column. The vapor content difference and the humidification efficiency were examined, and it was found that the air velocity and the temperature of the saline water had a significant impact on these parameters.

Furthermore, the vapor content difference is slightly influenced by the temperature of the inlet air. At water and air temperatures of 75 °C, the maximum experimentally measured vapor content difference of the air was 222 g/kg of dry air. Other geometrical parameters, such as column diameter, water head height, orifice number, and diameter, were not taken into account. It is noteworthy to mention that Treybal [7] and Lydersen [13] have numerous empirical correlations for these parameters. Therefore, before utilizing bubble columns in HDH systems, an ideal design and performance evaluation study can be completed.

Wetted-wall towers have been employed by Müller-Holst [17] and Orfi et al. [14] as humidifiers in HDH systems. A wetted-wall tower is a vertical pipe with a thin layer of water flowing downward and air flowing either co-currently or counter-currently.

A weir disperses the water flow around the inner perimeter of the tube, soaking the inner surface of the tube as it travels. Water is fed into the top of the tower. These devices have been employed in theoretical investigations of mass transfer because they allow for precise calculations of the contact area. Warm water was applied to polypropylene fleeces that were hanging vertically in Müller-Holst's system [17] and trickled down. Through the humidifier, the air moves in a countercurrent flow to the brine and saturates at the outlet. However, Orfi et al.'s wetted-wall humidifier [14] employed a different design. To improve the heat and mass exchange process, they covered the wooden vertical wetted-walls with a cotton wick to reduce the water flowing 23 velocity and use the capillary effect to keep the vertical walls always wetted. Their design shows higher performance with about 100 % humidification efficiency.

Packing is usually used to increase the humidification efficiency. This helps by increasing the contact area, contact time, and water droplet dispersion. Packing bed towers are devices that hold packing material, and cooling towers are specific kinds of devices used to cool water. These are vertical packing material-filled columns with water sprayed at the top. The airflow is arranged in a cross-flow or counter-flow pattern. Due to their greater efficacy, packed bed towers have been employed by numerous researchers as a humidifier in HDH desalination systems. Additionally, various packing materials have been employed. The performance of a packing in terms of heat and mass transfer, water quality, pressure drop, cost, and durability are the factors that affect the decision. According to Wallis & Aull [15], there has been a slow shift in the fill types utilized in packed bed towers over the past 30 years. The introduction of film fills, which offer noticeably better thermal performance by increasing the water-to-air contact area and lowering the pressure drop, has been the most notable change.

However, in HDH desalination application, due to high fouling potential, these benefits are forfeited and the older splash-type fill packing is used. Mirsky and Bauthier [16] presented a history of the development of packing materials while Aull &Krell 17] investigated the performance of various film-type fills. The Merkel, Poppe and epsilon- NTU heat and mass transfer methods of analysis are the cornerstone of cooling tower performance evaluation.

2.6 Dehumidifier designs

The types of heat exchangers used as dehumidifiers for HDH applications vary. For example, flat-plate heat exchangers were used by Müller-Holst et al. [17]. Others used finned tube heat exchangers ([16], [18] & 12]). A long tube with longitudinal fins was used in one study [21], while a stack of plates with copper tubes mounted on them in another study ([22] & [23]) used a horizontal falling film-type condenser. Direct contact 25 heat exchangers were also used as a condenser in some other studies [24] in combination with a shell- and-tube heat exchanger to provide enhanced condensation and improved heat recovery for the cycle.

For Muller-Holst's HDH system, [17] double webbed propylene slabs were used as a flat plate heat exchanger. The distillate trickles into the collecting basin as it flows down the plates. Transferring heat to the chilly seawater flowing inside the flat plate heat exchanger allows for heat recovery. The condenser's seawater temperature rises from 40 to 75 degrees Celsius. In a related study, Chafik ([16] & [18]) heated seawater with the humid air before pumping it to the humidifiers as a coolant. Three distinct stages of condensation each involved the use of three heat exchangers.

To further dehumidify the air, a second heat exchanger is added at the seawater intake (low temperature level). The heat exchangers, also known as dehumidifiers, are air coolers with finned tubes. They created a theoretical model by calculating the heat transfer coefficients from the hot and cold sides of the heat exchanger using TRNSYS, and then they used those values to set the operating conditions of the system. It is significant to remember that aluminum is used for the fins and stainless steel is used for the frames and collecting plates due to the corrosive nature of seawater. Furthermore, extra care was taken to prevent distillate water leaks.

Farid et al. used various condenser designs in an HDH cycle ([21] & [25]). A long copper galvanized steel tube (3 m in length and 170 mm in diameter) with 10 longitudinal fins measuring 50 mm in height on the outside and 9 fins on the inside was used as the dehumidifier in a pilot plant constructed in Malaysia. A simplified stack of flat condenser consisting of two x one meter galvanized steel plates with twenty-six long copper tubes affixed to each side of the plate to offer a substantial surface area was employed in another location. Large condenser sizes were used, especially to get around the low heat transfer coefficients on the water and air sides caused by low water flow rates and relatively low air velocity.

Another study by [22] reported on two types of condensers. For the bench and pilot units, these were made of galvanized steel plates. A copper tube with an OD of 11 mm and a length of 18 m was welded in a helical pattern to the galvanized plate within the pilot unit. In the bench unit, the tube's outside diameter and length were 8 mm and 3 m, respectively.

One or more condensers were mounted vertically in one of the ducts for each unit, connected in series. The condenser in one unit was just a 3 m diameter, 170 mm long cylinder composed of galvanized steel plates. The cylinder was soldered with ten longitudinal fins on the outside and nine identical fins on the inside. The outside and inside fins measured 50 mm in height. The plate used to create the fins and the cylinder had a thickness of 1.0 mm. A copper tube with an inside diameter of 9.5 mm was soldered onto the cylinder's surface. In [27]

Two solar heaters, one for heating water and the other for heating air, were part of the system Orfi et al. [14] used. The condenser, which utilizes seawater for cooling, is made up of a rectangular-shaped chamber. The feed water flows through two rows of long copper cylinders in this structure. The cylinders' exterior was soldered with longitudinal fins. The condenser's heat- transfer surface area is 1.5 m2, and its coil is 28 m in total length.

A few researchers ([14], [26] & [27]) employed packed bed direct contact heat exchangers because the presence of non-condensable gas severely reduces the heat transfer from film condensation. The desalinated water, from which some is recycled and sprayed in the condenser, is cooled using an additional shell and tube heat exchanger. The dehumidifier's governing equations are explained in differential form by Threlkeld [28]. Pacheco-Vega et al. have also summarized design correlations for heat transfer coefficients and friction factor that can be applied to dehumidifiers [29][28], The conventional technique, which was created by McQuiston [30], takes into account finned-tube multi row multi-column compact heat exchangers and uses Colburn j-factors in conjunction with flow rate, dry and wet bulb temperatures, fin spacing, and other dimensions to predict heat and mass transfer rates.

While the moist air enthalpy difference is used as a driving potential under condensing conditions, the air side heat transfer coefficient is based on the log-mean temperature difference for the dry surface. Pacheco-Vega et al. [29] developed a trained network that directly predicted the heat rate of the exchanger using neural network techniques and the experimental data compiled by McQuiston. When compared to the method that used correlations of the heat and mass transfer coefficient and Colburn j factors, remarkably accurate results were obtained. Since the exchanger heat rate is what users ultimately want, they concentrated on it.

There was a noticeable increase in prediction accuracy when compared to the traditional j factors approach; for example, there was a reported 56.9% decrease in error for drop-wise condensation and 58.6% decrease in error for film-wise condensation.

Conclusion

Solar energy is a potential source of energy for desalination of sea water. Many researchers are working on this area for providing fresh and clean water using renewable energy without disturbing ecological system. Researchers are hopeful to get optimal solution for the process of desalination of sea water using solar energy to reduce scarcity of water at sea coast.

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