World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

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Review on advanced techniques in zero liquid discharge water desalination via humidification-dehumidification within thermally-driven transport reactors

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World Journal of Advanced Research and Reviews, 2024, 23(03), 1568–1579

Publication history: Received on 07 July 2024; revised on 15 August 2024; accepted on 17 August 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.23.3.2498

Abstract

The article examines an advanced zero liquid discharge (ZLD) desalination method focusing on humidification-dehumidification (HDH) in thermally driven transport reactors. The limited availability of water, particularly in dry locations, has prompted the advancement of several desalination techniques. Reverse Osmosis (RO) is a prevalent membrane technology in the market; however, it has restrictions regarding brine disposal. ZLD technologies strive to mitigate environmental consequences by transforming saltwater into drinkable water and precious salts while minimizing waste. Membrane Distillation and Crystallization (MD-C) is notable as a highly efficient Zero Liquid Discharge (ZLD) technique. Despite its high energy consumption, it can combine MD-C with renewable or waste energy sources to improve sustainability. Freeze Desalination (FD) was reviewed for its economic efficiency, especially when utilizing cold energy from liquefied natural gas (LNG). Hybrid systems that combine Forward Osmosis (FO) and membrane distillation with condensation (MD-C) can potentially improve water recovery and decrease energy usage. The HDH desalination process imitates the natural precipitation process, examines its ability to operate at low temperatures, and highlights its potential for integration with renewable energy sources. The review discusses the HDH design, the effect of salinity on its performance, and the different dehumidification technologies. It emphasizes the significance of creative methods in achieving sustainable water management.

Keywords: Water Desalination; Freeze Desalination; Zero Liquid Discharge; Humidification-Dehumidification 4; Renewable Energy; Sustainable Energy

1. Introduction

Water is a vital natural resource, yet it is fast diminishing due to human activity. Many nations, particularly those in dry regions, have reached the threshold where sustainable water delivery is becoming increasingly challenging. Several desalination methods have been developed in recent decades to address the issue of water shortage. Desalination using membrane technologies accounts for approximately 68% of the overall desalination capacity. This percentage continues to rise due to the rapid growth of the membrane market (Nakoa et al., 2016). However, owing to cost considerations, conventional membrane techniques like Reverse Osmosis (RO) have a maximum hydraulic recovery limit of 75% - 85%. Therefore, a minimum of 15% - 25% of saline water needs to be disposed of as brine (Cappelle et al., 2017). Regrettably, the predominant approach for disposing of brine is by direct discharge into the ocean or surface water, despite the well-documented harmful effects it has on ecosystems (Al-Absi et al., 2021). An approach to achieving sustainability is the creation of zero-liquid discharge desalination (ZLDD) technologies. This efficient approach can transform saltwater into drinkable water and valuable salts without producing any waste.

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Freeze Desalination (FD), a new technique, having a cost-effective alternative for water recovery. FD stands for freeze desalination, which is the method of obtaining fresh water by collecting ice crystals from cold saltwater (Janajreh et al., 2023). According to Kalista et al. (2018), producing water by Freeze Desalination (FD) is more cost-effective than distillation since the latent heat of ice fusion is just 1/7 of that required for water vaporization. Furthermore, the energy expenditure can be further decreased if the cryogenic energy for FD is sourced from waste energy. Singapore imports around 6 million tons per year (Mtpa) of natural gas (NG) from other countries (Memon et al., 2014). In order to facilitate transportation, natural gas (NG) is kept in a liquid state at approximately -162 °C. Therefore, it is necessary to convert it back into a gaseous state at LNG terminals before distributing it to consumers. LNG possesses a low temperature and high energy density, resulting in a significant quantity of high-quality cold energy being stored throughout the re-gasification process. This makes LNG an ideal cooling source for FD (Wang, P., & Chung, T. S., 2012). However, FD is susceptible to elevated levels of salt concentrations (Da Lio et al., 2015). Ice crystals produced during freeze-drying have a significant surface energy and a vast specific surface area as a result of their microscopic dimensions. Consequently, salts have a tendency to stick to the surfaces of ice crystals. To remove these salts from the ice crystals, it is necessary to use pure water (Jimenez-Gomez et al., 2022). Applying a high salinity feed will result in the adsorption of many salt crystals onto ice surfaces. Hence, the excessive usage of washing water counterbalances the production of clean water from ice, rendering the technique economically impractical. In contrast, the performance of MD-C is hardly influenced by the salinity of the feed. Hence, FD and MD-C are complementary to one another, and their combination may be utilized to enhance water recovery while minimizing energy usage. In 2012, Wang et al. introduced the idea of combining FD with DCMD for the purpose of desalination. The hybrid system successfully attained a water recovery rate of 71.5%, which is considered high, and the quality of the water met the drinking water standards set by the World Health Organization (WHO). Furthermore, the study also showed that the use of LNG cold energy significantly decreased the overall energy expenditure (Ghaebi et al., 2017). Chang et al. examined the practicality of an energy-efficient FD Vacuum Membrane Distillation (VMD) hybrid system that operates on renewable energy sources. The system obtained a water recovery rate of 74%, and the heat obligation could be fulfilled by either using solar panels or re-gasifying LNG (Ghaebi et al., 2017).

Membrane distillation and crystallization (MDC) have been suggested as a means to accomplish Zero Liquid Discharge (ZLD) (Choi et al., 2019). Membrane Distillation (MD) is a thermally induced process that entails the movement of water vapor via a membrane (Deshmukh, A., & Elimelech, M., 2017). MD is a unique separation technique that allows for a theoretical rejection rate of 100% for non-volatile substances. Additionally, MD is less affected by changes in feed concentration. MD stands out from other pressure-driven membrane-based separation methods, and these benefits ensure that it is particularly well-suited for treating water with high salinity (Goh et al., 2016). In an MD-C system, the primary use of MD is water reclamation, resulting in a concentrated solution from MD being transferred to a crystallizer, resulting in valuable salt crystals being separated and removed (Das et al., 2021). Achieving a zero-discharge state is accomplished by reintroducing the crystallizer brine into the MD system and mixed with the feed solution for the subsequent water and salt recovery cycle. Nevertheless, the MD-C method is hindered by its high energy consumption (Lu et al., 2019). An effective option is to integrate it with renewable energy sources or utilize low-grade waste energy.

Due to the rising need for freshwater, the worldwide capacity for desalination has significantly expanded in recent decades. Desalination, with a production capacity of over 100 million m^3/day (Virgili, Pankratz, and Gasson, 2016), has emerged as a dependable provider of potable water. The highlighted worldwide desalination capacity is faced with difficulties in treating brine. This phenomenon arises due to the prevalence of various desalination methods, including reverse osmosis (RO), multi-stage flash desalination (MSF), and multi-effect distillation (MED).

The scarcity of potable water is a pressing worldwide concern, exacerbated by fast urbanization, population increase, and economic expansion (Dos Santos et al., 2017). By 2030, there will be a significant shortfall of 40% in the global water supply (Hejazi et al., 2014). Creating cost-effective and high-performing small-scale desalination machines might be a potential solution to tackle this issue. Conventional Solar Stills are economical means of generating clean water, but research into other technologies to enhance efficiency is ongoing.

Humidification-dehumidification (HDH) desalination has attracted considerable attention among these technologies since it may function at low temperatures and utilize sustainable energy sources such as solar and geothermal power. HDH system is primarily designed to replicate the natural precipitation cycle. It comprises a humidifier, a dehumidifier, heaters, pumps, and piping. This system may be classified into water-heated and air-heated cycles, with additional categorizations based on the arrangement of water and air loops (Lawal and Qasem, 2020).

Integrating HDH systems with other thermal systems, such as refrigeration, can enhance performance by increasing freshwater production, cooling effects, and power generation. This strategy also aids in preserving and optimizing energy use. The performance of HDH systems is strongly affected by salinity. Elevated salt levels can impair the effectiveness of water production, and efficiently controlling and reducing salinity in a closed-water cycle is essential for maintaining optimal performance (Huang et al., 2020).

2. Literature Review

2.1. HDH Desalination Processes

Desalination facilities produce highly concentrated brine as a byproduct, which presents significant environmental issues. Implementing efficient brine management techniques reduces brine and purifies water to mitigate ecological harm and decrease expenses. HDH desalination can effectively treat highly salinized water and reuse industrial wastewater, making it an attractive alternative for zero liquid discharge applications. This study examines the HDH desalination processes, analyzing the impact of salinity on water productivity and system performance. It also investigates the correlation between salinity and operational factors. Additionally, it delves into the ecological consequences of brine and the most efficient techniques for treating salt.

2.2. Zero Liquid Discharge (ZLD) Systems

ZLD, or Zero Liquid Discharge, is a classification of water treatment methods designed to minimize effluent and produce purified water suitable for reuse and irrigation purposes. These systems utilize advanced techniques to treat wastewater effectively, cleaning and recycling nearly all the received wastewater (Yaqub and Lee, 2019).

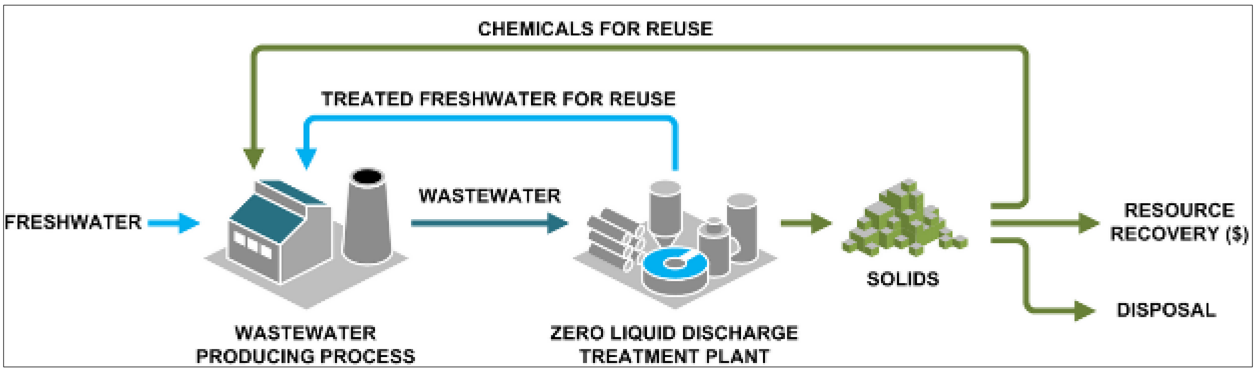


Figure 1 A zero-discharge process diagram that highlights wastewater from an industrial process converted to solid and treated water for reuse via a ZLD plant.

ZLD technologies help industrial facilities comply with discharge and water reuse standards. It allows them to adhere to government regulations regarding discharge, achieve water recovery, and extract valuable materials such as potassium sulfate, caustic soda, sodium sulfate, lithium, and gypsum from wastewater streams. Thermal technologies, such as evaporators (including multi-stage flash distillation), multi-effect distillation, mechanical vapor compression, crystallization, and condensate recovery, are the traditional methods to achieve zero liquid discharge (ZLD). However, ZLD plants generate solid waste by reducing the use of natural resources and minimizing waste generation.

Again, zero-liquid discharge (ZLD) is frequently associated with the circular economy and cost reduction concept. It manages the quantity of trash. Alternatively, raw materials and by-products can be reclaimed for reuse or commercialization. Microfiltration and ultrafiltration units are deployed frequently as pre-treatment methods. On the other hand, reverse osmosis is also employed as the treatment procedure to retrieve around 80% of the water and concentrate a separate liquid stream. Subsequently, thermal separation methods, such as vacuum evaporation and crystallization concentrate, the waste generated from membrane technologies that cause potential applications as raw materials or energy sources.

Vacuum evaporation is a highly dependable, long-lasting, and effective method that may generate up to 99% pure water while minimizing waste by utilizing its exceptional concentration capability. Evaporation and crystallization are crucial in all zero liquid discharge systems due to their indispensability.

Table 1 Brine Treatment Technology Methods (Eltawil, et al., 2008)

Brine Treatment Technology	Electrical Energy (KWh/m3)	Thermal Energy (kWh/m3)	Total El. Equivalent (kWh/m3)	Typical Size (m3/d)	Investment ($/m3/d)	max TDS (mg/L)
Multistage Flash	3.68	77.5	38.56	<75,000	1,800	250,000
Multi-Effect Distillation	2.22	69.52	33.50	<28,000	1,375	250,000
Mechanical Vapor Compression	14.86	0	14.86	<3,000	1,750	250,000
Electrodialysis	6.73	0	6.73	/	/	150,000
Forward Osmosis	0.475	65.4	29.91	/	/	200,000
Membrane Distillation	2.03	100.85	47.41	/	/	250,000

2.3. Humidification-Dehumidification (HDH) Desalination System

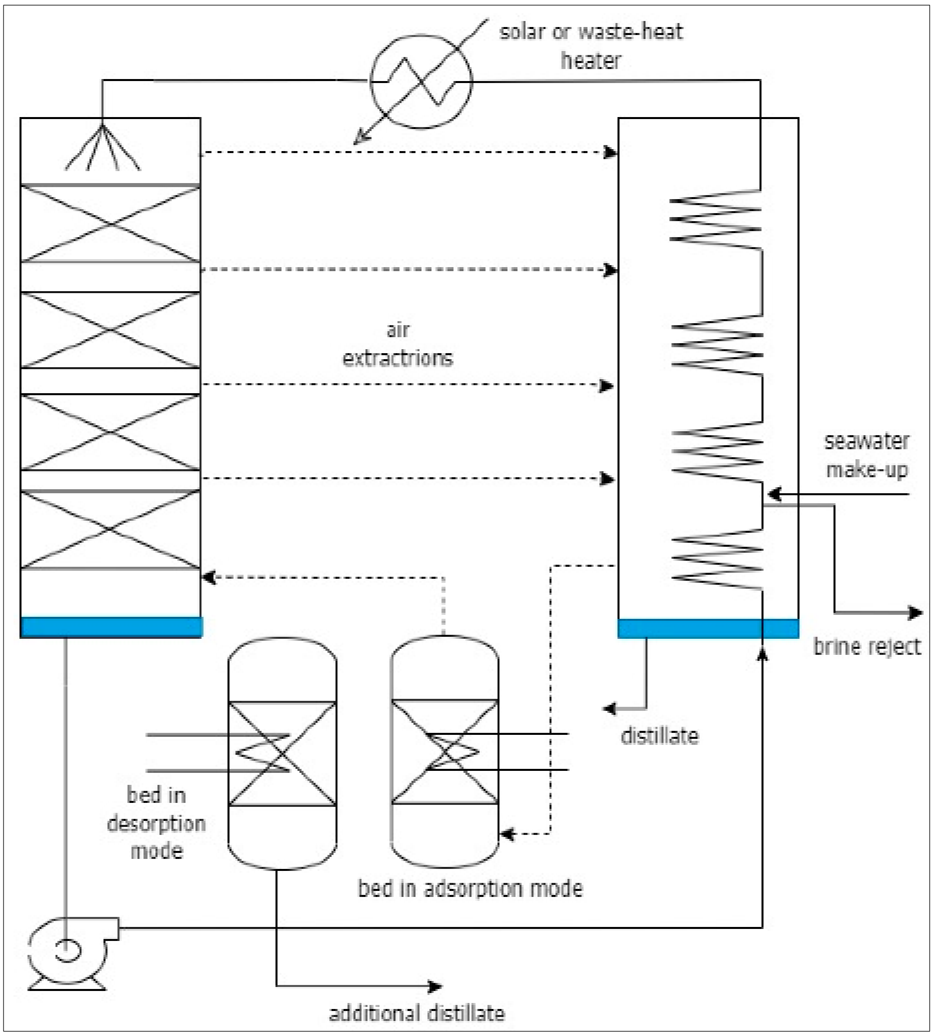


Figure 2 The user is requesting a process flow diagram of an HDH-AD desalination process that is combined with a two-bed unit for the adsorption and desorption of water vapor. (El-Maaty et al., 2024)

Integrating HDH systems with various technologies can significantly enhance cycle performance. This study will not include basic coupling/hybridization methods, but more technologies aligned to produce water, energy, cooling, or a combination of these, either working in series or parallel. For this purpose, we propose referring to the following published works (Ayati et al., 2020).

In a recent study, El-Agouz et al. (2018) examined the efficiency of a solar HDH system combined with a desiccant wheel in an open-air open-water setup. This setup included both an air sun heater and a water solar heater. The Mechanical Engineering Department of King Fahd University (Qasem et al., 2019) has thoroughly investigated the reference system for desiccant-improved HDH. The researchers developed and studied HDH systems that use desiccants. They also examined how to optimize the thermodynamics of the multi-stage process. A mathematical model achieved thermodynamic equilibrium in HDH systems with zero-extraction, multi-extraction, and infinite-extraction. This model was based on an approach previously reported by Lienhard's group (McGovern et al., 2013). Figure 2 is a simplified schematic illustrating this procedure. The desiccant removes moisture from the air by absorbing ambient humidity.

Another example of integrating HDH systems is the application of adsorption-based technology. Ng et al. (2013) suggested employing adsorption devices to absorb low-grade waste heat. These devices can generate crucial outputs, such as cooling, freshwater, and moisture. An adsorption unit can effectively remove water from the air without being constrained by the thermodynamic and transport restrictions often encountered during condensation. The adsorption (AD) cycle mimics a desalination process when a saline water evaporator is connected. Ng et al. (2015) granted a patent for a device that utilizes silica gel to convert saltwater into freshwater using adsorption, pioneered the first integrated process combining adsorption (AD) and multi-effect distillation (MED), with adsorption (AD) serving as the low-temperature bottom cycle to improve overall system productivity. The MED-AD research exhibited a significant enhancement in the output of product water in comparison to the standalone multi-effect distillation (MED) cycle (Ng et al. 2015). This enhancement can be attributed to the increased scope of permissible operating temperatures. In another research, Messer et al. (2021) found that spray humidification is considerably more energy-efficient than conventional venturi nozzle humidification, resulting in a 20-30% reduction in energy utilization. When spray humidification compared with boiling humidification, the energy savings were significantly higher, with spray humidification being 60-70% less energy intensive. This innovation showcases the potential of spray humidification as a more environmentally friendly technique for water vaporization in several applications.

Capocelli et al. (2023) suggested a comparable broadening of the operational temperature range for a combined HDH-AD system. They proposed an improved iteration of the closed-water closed-air cycle technique by including a water vapor adsorption phase into the HDH cycle. Figure 2 depicts a simplified schematic of the HDH-AD system, comprising a two-bed unit designed for the adsorption and desorption of water vapor. In this integrated process, the dehumidification unit of a multi-stage HDH system sends saturated air with moisture at the lowest temperature to a dehydration unit. This system utilizes adsorption beds arranged in a thermal swing adsorption/desorption arrangement to eliminate moisture from the air. Adsorption reduces humidity, and the air with reduced moisture is sent to the humidification process. This approach enables the temperature of the brine at the bottom to decrease to a level below that of the cold source, such as seawater. So, expanding the temperature range of the HDH allows for higher production out of distillate using the same external thermal source as the previous approach.

The process entails the utilization of a humidification tower, in which humid air flows counter to the direction of the seawater. The humidifier is comprised of a densely packed bed that has either randomly or systematically arranged packing. This arrangement facilitates efficient movement of heat and mass between the gas and liquid phases. During the dehumidification process, the air moves downwards and is cooled to collect the distilled liquid and heat the flowing saltwater in the tubes. According to McGovern et al. (2013), intermediate air extraction improves the efficiency of the cycle and make it easier to recirculate brine. The distillate might be acquired throughout the dehumidification process or at the condensation stage. The humid air leaving the dehumidification section passes through a fixed bed operating in adsorption mode, where it is captured by a hydrophilic porous material, effectively extracting moisture from the air. Another fixed bed concurrently improves the recovery of more distillate by regenerating the adsorbent. Both beds are connected to cooling and heating systems. The desiccated air is then recirculated to the humidification portion, maintaining a level below its saturation point.

2.4. Dehumidifiers (Condensers) in HDH Systems

When building a thermal system, it is frequently essential to forecast the heat transfer rates of heat exchangers under specified operating circumstances to make appropriate decisions. Heat exchangers are sophisticated devices because of their elaborate design and the vast physical processes involved in heat transmission. Several empirical investigations have been carried out to examine the specific heat and mass transfer characteristics of dehumidifying heat exchangers.

A theoretical and practical investigation was undertaken by Amer et al. (2209) on a condensation tower with dimensions of 200 cm in height, 40 cm in length, and 50 cm in breadth. The condenser contains a copper tube that is coiled and measures 15 meters in length. The outside diameter of the tube is 1.27cm. Fins are employed to augment the surface area of the condenser, leading to a combined surface area of roughly 6 m^2 for the coil and fins.

Zhania et al. (2010) investigated a novel solar desalination prototype that utilized the principle of humidification-dehumidification. The evaporation chamber houses many horizontal copper tubes with different inner and outer diameters. These tubes have microscopic holes (1.5 mm in diameter) on their upper surface, which act as pulverizers for hot salt water. The surface of each tube is coated with a viscose textile material to increase the area of contact between air and water. It helps to improve evaporation and avoid mixing hot salt water with fresh water in the condensation chamber. The lower part of the evaporation chamber, equipped with a ferry, has dimensions of 0.6 × 0.7 × 0.34 m. This ferry collects the brine, which can be reused or discarded based on its salinity levels. The collection process is possible by an underwater pump. The evaporation chamber features a rectangular cross-section with dimensions of 0.6 meters by 0.7 meters and a height of 1.37 meters.

Nafey et al. (2004) employed an air cooler heat exchanger and an extended surface crossflow cooling coil that functioned as a dehumidifier. The concentrated freshwater is channeled through a tube into a container, while the cooling water flows through the enlarged surface tubes. The system consists of 64 copper tubes, each measuring 46 cm in extended length of an aluminum sheet that is 0.5 mm thick. This configuration results in a total surface area of 20m^2.

Hermosillo et al. (2011) investigated the water desalination process using air humidification. The condenser in their investigation is a rectangular prism with a cross-sectional area of 0.093025 square meters and a length of 0.335 meters. Internally, the system consists of a liquid-gas heat exchanger comprising 105 vertically oriented tubes for water flow and 57 horizontally positioned fins for airflow. This arrangement results in a combined heat exchange surface area of 3.5m^2. The evaporator possesses comparable proportions and is 0.40 meters in length.

Yamali and Solmus (2008) employed three air cooler heat exchangers including copper tubes and corrugated aluminum fins for the purpose of dehumidification. The coolers were linked in a series configuration using copper tubing. The surface area of each condenser is 3.5 m^2, resulting in a total surface area of 10.5 m^2. The dehumidifier's heat exchanger, constructed from 2 mm thick galvanized steel with dimensions of 40 × 47 × 34 cm, was carefully positioned inside an insulated metal box and tightly welded together to reduce air leakage and prevent heat gain. Nawayseh et al. (1995) determined that in order to efficiently harness the latent heat of water condensation, a substantial condenser area is necessary.

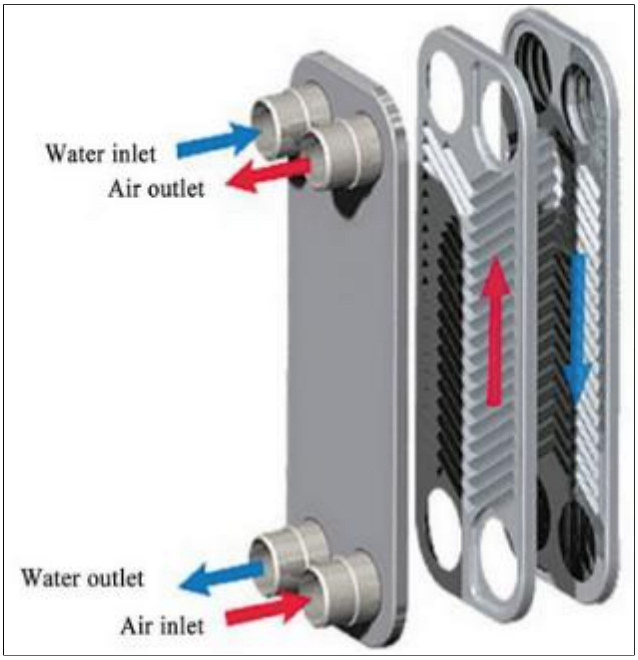


Figure 3 Plate fin tube heat exchange (kabeel et al., 2013)

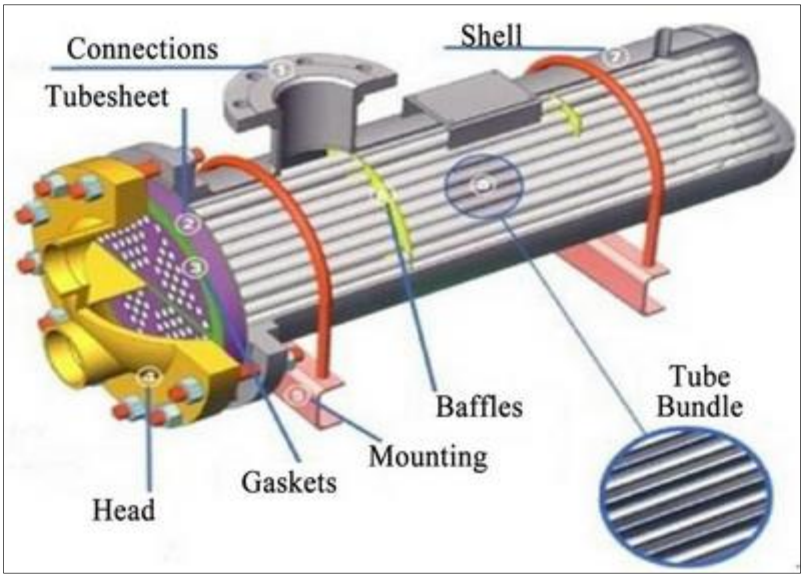


Figure 4 Shell and tube heat exchanger (kabeel et al., 2013)

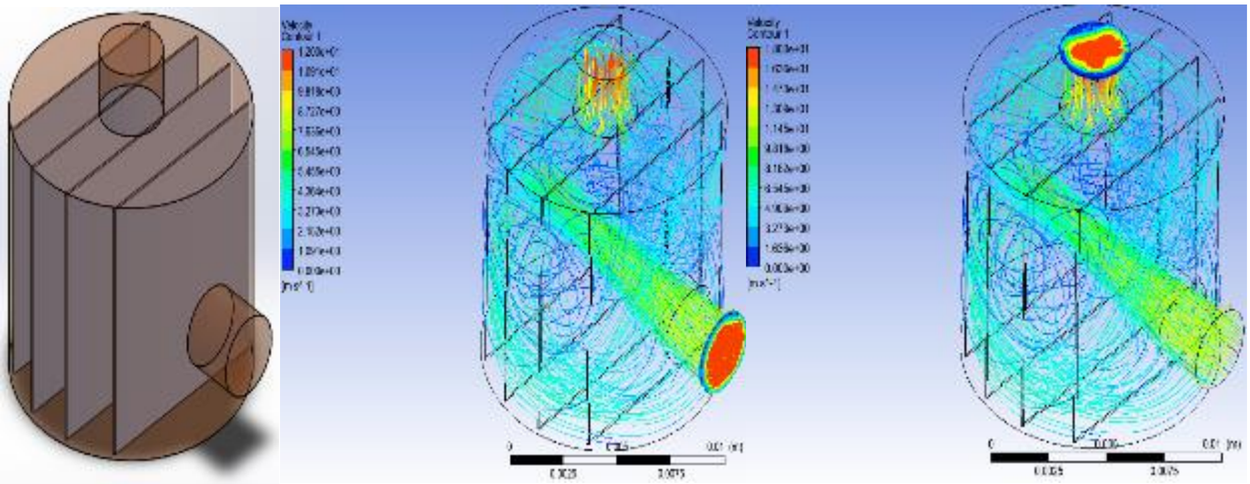
The fin tube heat exchanger of the plate, displayed in Figure 3, has undergone comprehensive scrutiny regarding its efficacy in extracting moisture from evaporators. McQuiston (1980) investigated the relationship between the overall j factor, known as the sensible j factor, and the parameters of airflow and heat exchangers. He demonstrated that the accuracy of predicting the condensate flow rate is affected by changes in the airflow rate and fin spacing. In 1973, Rich performed research to examine how the spacing of fins affects heat transmission in heat exchangers with many rows of smooth plates and tubes. The findings indicate that the heat transfer coefficient remains constant within 3 to 21 fins per inch, assuming a fixed air mass flux. Rich's (1975) research primarily examines how the number of rows affects heat transmission efficiency. The results indicated that the average heat transfer coefficient for a deep coil can either exceed or fall below that for a shallow coil, depending on the Reynolds number.

McQuiston (1980) introduced a technique for evaluating the efficiency of a tin plate having a uniform cross-sectional shape. The study determined that mass transfer significantly reduces the effectiveness of the fin, particularly in situations involving very humid air and low evaporator temperatures. Saboya and Sparrow (1976) found that a boundary layer on the front edge of the tin plate and a vortex system in front of the tubes greatly enhance the rates of mass transfer. Subsequently, McQuiston (1980) investigated the thermal and fluid dynamics of plate-fin tube heat exchangers indicating that both the overall j factor and the sensible j factor were correlated with a metric that incorporates tube diameter, tube transverse distance, and fin spacing. Furthermore, he developed a correction factor for heat exchangers with several rows by applying the j factors especially designed for plate-fin tube heat exchangers with four rows.

Webb et al. (1985) devised a theoretical model to predict the condensation coefficient on horizontal integral-fin tubes designed particularly for surface tension-induced drainage. Eckels and Rabas (1987) found a relationship between the wet and dry sensible heat transfer coefficients and the transverse velocity of condensing water vapor. Their research suggests that the transverse velocity significantly affects the transmission of heat, mass, and momentum in air-cooling processes. As the standard face velocity rose, they saw a clear and consistent increase in both wet and dry sensible heat transfer coefficients. Coney et al. (1989) performed a numerical investigation on the efficiency of fins in the presence of condensation from moist air. The researchers reported the results of the average condensate heat transfer coefficients and overall air heat transfer coefficients are related to the bulk air velocity. Jacobi and Goldschmidt (1990) later developed a mathematical connection that characterizes the enthalpy Colburn j factor. This factor measures the effectiveness of heat and mass transmission in integrated high-finned tube evaporators or dehumidifying heat exchangers that operate at low Reynolds numbers. Their findings indicate that condensate retention at low Reynolds numbers has a detrimental effect on the sensible j factor but significantly enhances the overall heat transfer rates during condensation.

Mirth and Ramadhyani (1993) conducted a study that showed wet-surface heat transfer coefficients depart from the correlation seen for dry surfaces. The patterns of whether wetted surfaces enhance, or hinder heat transmission remain ambiguous. Furthermore, they examined the thermal and fluid characteristics of heat exchangers equipped with undulating fins and where the observed Nusselt numbers demonstrate a significant degree of responsiveness to changes in inlet dew point temperatures. More precisely, the Nusselt numbers exhibit a reduction while the dew point temperatures demonstrate an increase. Fu et al. (1995) found that when the relative humidity of the intake increased, there was a noticeable decrease in the wet sensible heat transfer coefficients in dehumidifying heat exchangers using louver fins. In contrast, Seshimo et al. (1989) found that the Nusselt number showed little sensitivity to the inlet conditions.

Wu and Bong (1994) devised an analytical approach for determining the total efficiency of a partially wet fin. It is recommended that the total efficiency for the dry and moist regions of the fin be calculated separately. Efficiency as a performance function can be output by the interaction and differential created between the inlet and outlet variables of a water reactor's velocity, pressure, and mass flow rate as depicted in Figure 5.



(a) (b) (c)

Figure 5 (a) Mesh wick, (b) Velocity at the inlet and (c) outlet (Uwaoma and Balogun, 2024)

The velocity profile of the inlet shows a uniform velocity of 12m/s while the velocity value at the wall is 0m/s which shows no slip condition. The velocity at the wall of a component is zero. The velocity at the outlet of the mesh wick component increased to 18m/s from 12m/s. The velocity moving to the walls of the outlet region reduces gradually towards the wall of the outlet. It was observed the velocity at the end region was enhanced, showing the presence of porous wick facilitating the velocity profile of hydrodynamic fluid flow. The velocity of thermal fluid flow is a fundamental parameter that influences many aspects of fluid flow, including flow rate, pressure distribution, boundary layer characteristics, turbulence, and drag forces (Uwaoma and Balogun, 2024). Nevertheless, the effects of face velocity where the maximum condensate flow rate occurs had not been discussed in their work. Therefore, Wicking action requires the migration of fluid through a porous surface via capillary action, influenced by factors like wick thickness and fluid properties. Uwaoma (2021) developed a thermal compressor that uses wicking action to transport fluid, aiming for a precise flow rate of 50 g/s, and discovered that the 250-mesh nano-structured copper wick outperformed the best due to enhanced surface energy. This research highlights the importance of designing effective wick structures for optimal performance in thermal management systems.

2.5. Key challenges and future consideration

Additional system design and operational variable strategies that require further investigation include the following: The challenges in HDH suggest the need for more experimental research on large-scale implementation of HDH driven by renewable energy, employing a comprehensive range of designs, sizes, insulators, and packaging to simulate each system component, resulting in significant reductions in investment and operational costs. A water desalination system can achieve commercial viability by using the waste heat generated by industrial processes or power plants as a heat source.

2.6. Glossary

- AD Adsorption
- DCMD Direct Contact Membrane Distillation

- FD Freeze Desalination
- FO Forward Osmosis
- HDH Humidification-Dehumidification
- LNG Liquefied Natural Gas
- MD Membrane Distillation
- MD-C Membrane Distillation and Crystallization
- MED Multi-effect Distillation
- MSF Multi-stage Flash desalination
- NG Natural Gas
- RO Reverse Osmosis
- WHO World Health Organization
- ZLD Zero Liquid Discharge
- ZLDD Zero Liquid Discharge Desalination

3. Conclusion

The Humidification-Dehumidification (HDH) system is highly effective for producing potable water from brackish and waste streams, often using sustainable energy sources. This research examines the unique characteristics of HDH, highlighting its simplicity, cost-effectiveness, and low-maintenance nature, particularly when integrated with other processes for optimal efficiency. Various improvements, such as multi-stage humidification, energy recovery techniques, and pressure manipulation in the humidifier and dehumidifier, have been explored to enhance HDH system performance, with significant advancements seen in the integration of adsorption cycles and multi-effect distillation for eco-friendly desalination. FD offers significant energy savings compared to traditional distillation methods, its efficiency can be hindered by high salinity levels, which necessitate extensive washing to remove salt from ice crystals. To address this, hybrid systems combining FD with processes like Membrane Distillation (MD) have been developed, achieving high water recovery rates while minimizing energy consumption. These hybrid systems not only enhance water quality to meet drinking standards but also leverage renewable energy sources, making them a promising solution for sustainable desalination.

Compliance with ethical standards

Acknowledgement

The authors also extend special thanks to Water and Energy Technologies Laboratory (WET Lab) for all the support.

Disclosure of conflict of interest

The authors declared that there is no known conflict of interest to be disclosed.

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