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Experimental investigation of humidification-dehumidification desalination system with corrugated packing in the humidifier

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HIGHLIGHTS

- The performance of HDH desalination system with anew packed bed humidifier is experimentally investigated.
- The corrugated aluminum sheets (zigzag) packing is used in the humidifier.
- The maximum productivity of the unit attains 15 kg/hr.
- The air and cooling water mass flow rate exhibit a great effect on the dehumidifier effectiveness.

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ABSTRACT

The performance of a desalination unit using humidification-dehumidification technology with new corrugated packing aluminum sheets in the humidifier was experimentally investigated. The influences of operating variables on yield and performance are studied. Operating variables include the air and water temperature at entry to the humidifier, the humidifier water flow rate, the ratio of mass of water to air, and the cooling water flow rate into the dehumidifier. To conduct such a study, an experimental set-up was developed, including a packed bed humidifier, finned tube condenser, water heater, air heater, and other auxiliary devices. The results indicate that increasing the temperature of inlet water in the humidifier, the humidifier water flow rate, and the dehumidifier cooling water rate significantly increases the production of distilled water. However, a slight increase in the production of desalinated water is observed by raising the air temperature, while a specific air mass rate achieves the highest productivity. The inlet cooling water temperature significantly enhances the yield from 10 to 15 L/h as the inlet cooling temperature reduces from 28.5 °C to17 °C. Cost analysis of the developed system indicates that the total cost per one liter of fresh water is about $0.01.

1. Introduction

Water is the basic necessity of life. Humans need water for many purposes such as agriculture, domestic purposes, and industrial processes. The World Health Organization (WHO) recommends that one person should have no less than 15–20 L of fresh water per day for basic needs such as drinking, food preparation, personal hygiene, and the washing of clothes. However, this defined value cannot sustain various requirements and so should be increased to about 50 L per person each day [1]. Water scarcity is a global issue still being addressed till this day. Many countries are impacted and more than 700 million people around the world do not have access to clean drinking water [2]. Moreover, an increasing global population continues to raise the importance of the issue of water scarcity now and in the future. It is expected that by 2030, the world will need about 6900 billion cubic meters (Bm^3) of clean water. Nevertheless, the total available amount remains at only 4500 Bm^3 [3].

Numerous research studies were performed to investigate the conversion of salt water from the seas and oceans into fresh water using various desalination technologies such as vapor compression (VC), multi effect (ME), reverse osmosis (RO), multi-stage flash (MSF), and humidification-dehumidification (HDH). However, methodologies such as VC, ME, RO, and MSF are only suitable for large and medium capacities, and are too expensive to be applied to small capacities. In contrast, the HDH method is appropriate for a small capacity context. It was reported that the average specific energy consumption of the HDH method is about 150 kJ kg^{-1} of desalinated water, and the fuel consumption is around 3.5 L per cubic meter of distilled water production [4].

There are three different ways to classify HDH systems. The system can be categorized according to the energy source, the cycle

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configuration for water and air, or the types of heating systems for both water and/or air. Major elements of the HDH unit are the humidifier, the dehumidifier, and the heating system for both air and water. The productivity of these HDH systems is essentially reliant on entry water and air conditions, water and air flow rates, mass flow rates of cooling water and entry temperature, and geometrical features of both the humidifier and dehumidifier. Siddiqui et al. [5] studied two different set ups of the humidification- dehumidification desalination unit. The first set up did not contain a solar air heater to heat the ambient air before entering the humidifier, and did contain two electric heaters to heat the water. The second set up contained a solar air heater and an electric water heater. The results show that the productivity and the gain output ratios are increased in the second set up, where the unit contains one solar air heater and one electric water heater. They concluded that the cost per litter with the second set up was lower than with the first set up. Rajaseenivasan and Srithar [6] conducted an experimental study on the HDH unit by using a dual purpose solar collector (DPSC) to simultaneously heat the water and the air before it entered the humidifier. They reported that the yield of the unit is enhanced by increasing the air and water temperature. Chiranjeevi et al. [7] performed an experimental and numerical study on a two-stage humidification-dehumidification desalination system integrated with a cooling plant. Each stage contains an air preheater, humidifier, and dehumidifier. They concluded that increasing the hot water flow rate and its temperature improves the desalination output. In addition, the second stage increases the yield of fresh water.

Many types of humidifiers such as spray towers [8], bubble columns [9], and packed bed towers [10] are commonly used. Narayan et al. [11] reported that packed bed towers exhibit higher effectiveness owing to prolonged contact time between air and water and a larger area of air-water interface. The two main types of packing are film and splash packing. The film packing has a higher thermal performance than the splash packing, and so many researchers have used honey comb in the humidifier. However, this type of packing is difficult to clean due to the precipitation of salt that accumulates on it.

Kabeel and El-said [12] conducted an experimental study on a hybrid HDH and a single stage flashing evaporation unit. They used a pad humidifier with packing that consisted of polyvinyl chloride (PVC) rings of a column diameter of 0.45 m and a height of 0.8 m. In another study, Kabeel et al. [13] experimentally evaluated the performance of a solar HDH unit with natural and forced draft air circulation. The humidifier is a packed column with cellulose paper. In their work, the effect of forced circulation of the air up, down, and up-down on the performance of the unit was investigated. Their results indicated that forced down circulation results in a better performance than up and up-down circulation. In another study performed by Kabeel et al. [14], they reviewed the humidification-dehumidification desalination methods and concluded that it is the most appropriate method for small capacity water production. This method contains a small thermal grade requirement, and the necessary energy could be attained efficiently from solar energy. Furthermore, increasing the evaporator and condenser surface area leads to a major rise in desalinated water productivity. Dai et al. [15] established a unit with a cross flow packed bed humidifier and a large evaporation surface to improve mass and heat transfer. The performance of such a unit was stated to be mainly reliant on the temperature of entry water to the humidifier, and the flow rate of seawater and air. Furthermore, the unit's thermal efficiency was about 85%, while the waste energy could be used to power the system. Al-Enezi et al. [16] established a unit that included a plastic packed column humidifier, a heater to preheat the water from 35 °C to 45 °C, a cooling water cycle for the condenser, and an air heater. They investigated the impact of the humidifier inlet water temperature, air mass rate, and the temperature of cooling water on the mass transfer coefficient, and total heat transfer coefficient in the dehumidifier. The highest production rate was achieved at an elevated hot water temperature and a lower water cooling temperature. In addition, Nawayseh et al. [17] evaluated the mass transfer coefficient for two types of packing made from wooden slates with an inlet water temperature above 50 °C and compared those results with other packing types. The comparison revealed that the mass transfer coefficient depended on the type of packing. Muthusamy and Srithar [18] experimentally investigated the productivity of the HDH unit with several modifications. Their design included packed beds with two different materials in the humidifier to enhance the mass transfer process: saw dust, and a gunny bag. It was reported that the modified system significantly boosts the productivity of fresh water, for an equal input of power.

Yamalı and Solmus [19] performed an experimental investigation to estimate the influence of operating and geometrical variables and on the productivity of clean water in the HDH desalination unit using plastic packing. They reported that the yield rises with the elevation of both the entry water flow rate and the cooling water flow rate, and is unaffected by raising the mass rate of air. Orfi et al. [20] concluded that there is an optimum ratio of mass flow rate corresponding to the highest productivity of clean water based on their experimental and numerical study of the HDH desalination unit. Al-Hallaj et al. [21] conducted an experimental investigation to determine the production of desalinated water using a HDH unit with wooden packing. According to their results, the yield of fresh water was higher than with the use of the single-basin stills. Furthermore, using high air temperature with high forced circulation had an insignificant effect on the unit's performance.

In this paper, a new design for a packed bed humidifier is developed. The design includes corrugated aluminum sheets (zigzag) used in the humidifier to increase the surface area of water–air interface. This will significantly improve the mass and heat transfer process and allow for a longer contact time between water and air. In addition, this design displays a lower pressure drop than with the commonly used honeycomb and allows for easier maintenance and cleaning of the packed bed. The performance of the proposed HDH unit is investigated at different operating variables.

2. Experimental set-up

The outline of the investigated HDH desalination unit is represented in Fig. 1. Major parts include a humidifier, dehumidifier, storage tank, heater, pump, fans, flow meter (orifice), and temperature measurements associated with the piping and valves. Any type of energy source such as solar, waste, or geothermal can be used to heat the water. To facilitate the experiment, four electric heaters are used to heat the water inside the storage tank. Then, the water is pumped into the distribution pipes above the packing as shown in Fig. 1. The water flows from the lower end of the humidifier and returns once again into the storage

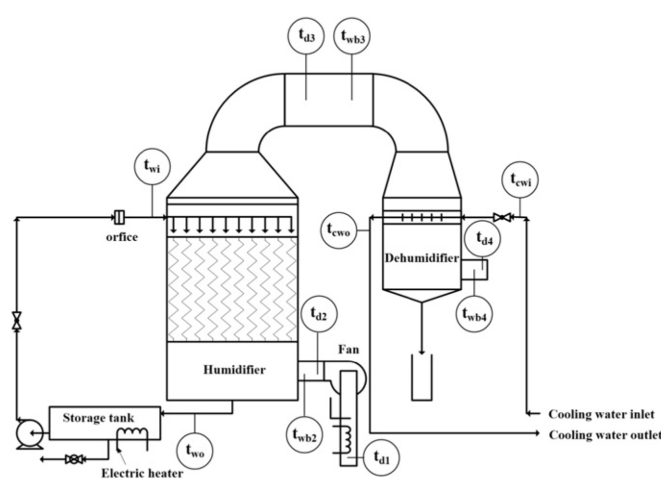

Fig. 1. Schematic diagram of HDH system.