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Energy and exergy analysis for a humidification–dehumidification desalination system integrated with multiple inserts

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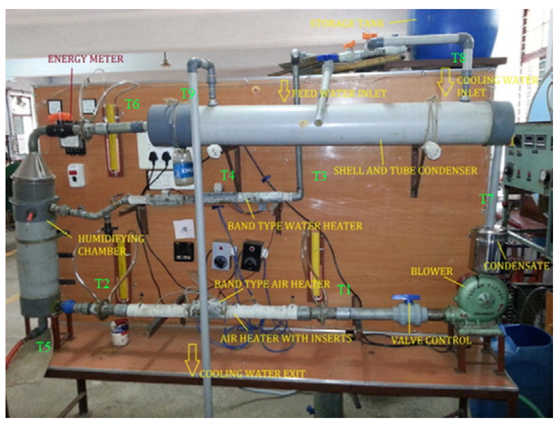
HIGHLIGHTS

- Developed an economical HDH desalination system for productivity enhancement.
- Inserts in air heater and de-humidifier augmented the productivity and system efficiency.
- Performance of the system optimized by using energy and exergy analysis.

GRAPHICAL ABSTRACT



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ABSTRACT

An experimental analysis is conducted to accelerate the productivity of the humidification dehumidification (HDH) desalination system. In the air heater region of the HDH desalination system, inserts namely (i) twisted tape in short length with tapered form, (ii) cut out conical turbulators integrated with internal fins arranged in convergent and divergent mode and (iii) half perforated circular inserts with an orientation angle of 45°, 90°, and 180° are tried out respectively with pitch ratio (PR) of 3, 4 and 5 to enhance the heat transfer rate in the air heater. Two types of packing materials, such as gunny bag and saw dust, are tested in the humidifier region accommodating the mass transfer rate. Also an attempt has been made to augment the overall heat transfer coefficient in the dehumidifier with spring insert for PR of 3 and 4. An energy and exergy analysis construed the quantity of effective utilization of energy with the modified HDH desalination system. The enhanced system produced 45% increase of productivity compared to conventional system of 0.340 kg/h. For the same input power, the modified system enhanced the heat output and productivity equivalent to a power saving of 40% and 13% respectively.

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1. Introduction

In the past several researches focused on creating an economical solution for providing potable water. Based on their investigations HDH desalination systems proved to be an economical solution. In order to enhance the performance of the HDH desalination system, various research works have been carried out.

Ghazi et al. [1] experimentally studied the effect of operating parameters such as temperature and flow rate of feed water, air and cooling water on the productivity of the HDH desalination system which consists of a plain electrical air heater and proved that the productivity increases with the increase of mass flow rate of air and decrease of cooling water temperature. Agouz [2] conducted the experiments to study the behavior of humid air based upon the effect of water temperature. The mass flow rate of water and saline water level in the tank were evaluated and suggest that temperature and mass flow rate of air and water influence the system productivity.

Guofeng et al. [3] investigated the performance of a solar humidification–dehumidification desalination system in which higher outlet air temperature and relative humidity increased the absolute moisture content of the air flow, which improved fresh water production of the unit under the same cooling condition. The water production test results show that the fresh water production increases as solar radiation strengthens, and the system water production can reach 1200 L/day, when the average intensity of solar radiation gets to 550 W/m^2.

Dai et al. [4] studied the effect of operating conditions such as flow rates, temperatures of feed water, air and cooling water in order to improve the performance of the solar humidification–dehumidification desalination system. Amer et al. [5] carried out detailed experiments with various operating conditions and several packing materials and showed that the system productivity increased with the increase in the mass flow rate of water. Guofeng et al. [6] designed a closed circulation desalination system and focused on studying and analyzing the collector area, cooling water flow rate, and seawater flow rate of the system.

Yamili and Solmus [7] studied the effect of mass flow rate and temperature of air, feed water and cooling water on the productivity of a solar HDH desalination system with a single and double pass solar air heater and proved that the double pass solar air heater showed an increased productivity of 8% compared with the single pass air heater. Hisham Ettouney [8] evaluated the characteristics of four configurations of HDH desalination system namely the conventional system, the mechanical compressor system, the desiccant system, and the membrane air drying system. Al-Hallaja et al. [9] has made an extensive study of combining the principle of humidification–dehumidification with solar desalination results showing an increase in the overall efficiency of the desalination plant. Dai and Zhang [10] investigated the performance of the HDH desalination system and found that the performance was strongly based on the temperature and mass flow rate of the feed water and process air.

The exergy analysis concept is widely recognized as a necessary tool to quantify the thermodynamic losses in a given system. Alhazmy [11] presented a theoretical analysis to estimate the minimum work required for a HDH desalination system. Shaobo Hou [12] conducted an exergy analysis of the components of a solar HDH desalination process and identified the solar collector as having the lowest exergy efficiency. Fawzi et al. [13] calculated the thermodynamic losses in a solar powered membrane distillation unit using the exergy concept. Karan et al. [14] investigated the HDH system to maximize the gained output ratio by minimizing the specific entropy generation of the cycle. Ashrafizhadeh et al. [15] conducted an exergy analysis in the HDH system and developed the equations for analyzing exergy in the system.

Eiamsa-ard et al. [16] investigated the performance of a double pipe heat exchanger fitted with regularly spaced twisted tape elements and proved that the heat transfer coefficient increases with increase in twist ratio and friction factor. Muthusamy et al. [17] investigated the effect of cut out conical turbulators with integrated fins on heat transfer and friction factor in a circular tube. Results showed that the turbulators with divergent mode enhance the heat transfer rate by 315% compared to a plain tube. Promvonge et al. [18] analyzed the V turbulators with a snail entry in the circular tube with the pitch ratio 2, 4 and 7 for the similar conditions. The arrangement with PR 3 shows the highest Nusselt number of 120 compared to the plain tube value of 30 for Reynolds number of 17,000 and the friction factor of 3.5, 0.2 observed for a tube with inserts and a plain tube respectively. Suresh et al. [19] experimentally studied the effect of heat transfer and friction factor characteristics in the circular tube using two wire coil inserts of pitch ratio 2 and 3 with the Al_2O_3/water nanofluid with 0.1% of volume concentration in transition flow. The Nusselt number increases up to 20% compared to the plain tube and the increased value of 45 observed compared to the plain tube Nusselt number of 12 for Reynolds number of 3000. Hsieh et al. [20] carried out experimental studies on heat transfer and flow characteristics for turbulent flow of air in a horizontal circular tube with longitudinal and cross strip inserts. They reported that the friction factor increase due to the inclusion of inserts was typically between 1.1 and 1.5 compared to the plain tube for the Reynolds number maintained between 6500 to 19,500 with respect to a bare tube.

Aforementioned works revealed that introducing inserts in the flow passage augments the heat transfer rate. Researchers carried out such experimentation in the application of the air heater and water heater and leaving a gap to apply this concept to the HDH desalination system. The objective of this present work is to achieve a higher performance in the HDH desalination system by introducing inserts in the air heater as well as in the dehumidifier of the existing HDH desalinaion system. An additional objective is to compare the performance of the HDH desalination system by using two different types of packing materials in the humidifier.

2. Description of the system

A humidification–dehumidification desalination system mainly consists of blower, air heater, water heater, and humidifier chamber and shell and tube condenser unit. The schematic sketch of the desalination system is shown in Fig. 1. The air heater consists of a galvanized iron pipe with 33 mm internal diameter with a thickness of 1.5 mm and 500 mm length which is insulated by asbestos rope to inhibit heat losses, and a 500 W band heater attached around the center of the air heater.

The water heater is made up of 13 mm diameter galvanized iron pipe with 1000 mm length covered in the center by the band heater with a capacity 1 kW. The humidifier chamber is made of polyvinyl chloride (PVC) tube of 152 mm diameter and 800 mm height. Packing materials are arranged in two layers as shown in Fig. 1. The shell and tube condenser with one shell and 5 tube passes is used as dehumidifier with 13 mm tube diameter and 1000 mm length and covered by the outer shell of 152 mm diameter.

2.1. Working of the system

The process air enters the air heater pumped by the blower, and heated by the electric band heater. Hot air then enters the humidifier and moves upwards. Hot saline water coming from the water heater is sprinkled downwards in the humidifier and collected in a saline water tank and sent back to Tank 1. The hot air coming upwards is humidified due to the heat and mass transfer between the hot saline water and the process air.

The moist air from the humidifier chamber is passed to the inner tubes of the shell and tube condenser and rejects its latent heat to the cold saline water (coming from Tank 2) which flows around the inner tubes of the condenser. Counter flow is maintained between the two fluids to achieve maximum heat transfer rate. The cold fluid (water) from the shell and tube condenser is collected in the hot water tank and sent back to Tank 1. Condensed distilled water from hot moist air is collected in the distillate tank. After reaching steady state, the