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Investigation on humidification dehumidification desalination system coupled with heat pump

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ABSTRACT

In this paper, a mechanical compression heat pump was coupled into the water-heated humidification dehumidification (HDH) desalination system, in which the condenser is applied to heat the seawater while the evaporator is considered to recover the carried heat from the discharged brine. In view of the integration mechanisms between the desalination unit and heat pump, mathematical models based on mass and energy equilibrium are built. Performance of the combined system, including the water production and gained-output-ratio (GOR), at the design conditions are first obtained. Moreover, the relevant influences from the prescribed critical parameters on the performance of the desalination system are simulated and analyzed. The simulation results show that the best performance of the coupled HDH desalination system, appearing as 82.12 kgh^{-1} for the water production and 5.14 for the GOR, is acquired at the balance condition of the dehumidifier. Two fully coupled cases, in which the heater or cooler is no longer required, when the air mass flow rate is located at 0.17 kgs^{-1} and 0.35 kgs^{-1}, are found. During the influence analysis, a best value of pressure ratio, PR = 4, is found due to a highest value of GOR as 5.14 although the relevant value of water production is attained as 106.53 kgh^{-1} when the pressure ratio is fixed at 5. Furthermore, it is also observed that a lower value of the pinch temperature difference for the condenser, higher values of effectiveness both for the humidification and dehumidification, are effective to elevate the water production and the corresponding thermal efficiency.

1. Introduction

As a result of the serious problems from water resource shortage, water producing methods and the relevant devices have drawn extensive attentions all over the world. Thereinto, as the important type to produce water, a lot of thermal desalination methods were advised and put into reality gradually, such as multi-stage flash (MSF) [1,2], multi-effect evaporator (MEE) [3] and mechanical vapor compression (MVC) [4]. However, the aforementioned desalination plants will be limited by the complicated configurations and the relevant large cost of energy and investments. Recent years, a very promising desalination method with high value of GOR, on the basis of the humidification and dehumidification processes, was proposed [5–7], and a lot of researches have been completed.

Rajaseenivasan [8] achieved a test study for an HDH desalination system with solar collectors, which were used both for water and air heating. The experimental results reported the related parameters during the water producing capacity, containing mass flow rate and operation temperatures. It was found that an overall efficiency of 67.6% with the concave turbulators can be obtained. Highest water production for the structures without turbulators, convex and concave turbulators were gained as 12.36, 14.14 and 15.23 $kg\,m^{-2}$ one day, respectively. Campos [9] constituted the mathematical models for an HDH desalination unit with cycling saturated air. Based on the experimental test, thermal parameters were investigated and optimized. With the validated theoretical models, a parametric investigation was accomplished to search the correlations between the water production and input boundaries. A bubble column humidification dehumidification desalination unit with the biomass as the driving force was proposed by Rajaseenivasan [10], and it mainly consisted of a bubble column humidifier, dehumidifier, a biomass stove and an air heat exchanger. Experiments were first completed in the bubble column humidifier to fix the water depth, bubble pipe hole diameter and water temperature. It was observed that the capacity of the humidification process was augmented with the ascent of some parameters, including the water depth, temperature, air mass flow rate, cooling water flow rate and the diameter for the bubble pipe hole. The experiment results showed that water temperature is critical to control the humidifier performance

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Nomenclature

Roman symbols

D_{con}	distance along the condenser (mm)
D_e	distance along the evaporator (mm)
h	enthalpy (kJ kg^{-1})
h_{fg}	latent heat (kJ kg^{-1})
H	total enthalpy (kW)
m	mass flow rate (kgs^{-1})
Q	heat load (kW)
S	concentration of seawater (gkg^{-1})
T	temperature (K)
w	humidity ratio (gkg^{-1})
W	power consumption (kW)

Greek letters

ε	effectiveness of the humidifier and dehumidifier
ϕ	relative humidity

Subscripts

a	air
b	brine
c	compressor
con	condenser
d	dehumidifier
da	dry air
e	evaporator
h	humidifier
i	inlet
m	maximum
o	outlet
r	refrigerant
sw	seawater
t	total
v	valve
w	water

compared to other parameters. Moreover, the scales of the bubble pipe hole diameter, water depth and temperature was determined resulting in a better specific humidity. Finally, a correlation was summarized to evaluate the mass transfer coefficient. Huang [11] introduced the open solution system to evaporate the solution with a more rigorous mathematical model for the humidifier. On the basis of the built programme for the whole system, theoretical simulation was completed to explore the impacts form important parameters on the final evaporation load and the thermal efficiency. It was found that the reflux ratio and inlet temperature of the solution into the humidifier were proportional to the relevant evaporation capacity, and an optimized air mass flow rate was discovered to maximize the evaporation capacity.

Heat pump is a thermal system with prominent performance of energy conservation due to a higher of coefficient of performance (COP) [12,13]. Actually, the combination of the heat pump and desalination process [14–16] have been applied to enhance the thermal performance of the water producing. Hawlader [17] proposed a novel desalination system powered by solar assisted heat pump, which was constituted with a single effect desalination unit and an existing solar assisted heat pump. The system were mainly made up of a condenser, evaporator, compressor, solar evaporator-collector, desalination chamber, feed tank, vacuum pump and distillate collection unit. Experiments were conducted through the system platform at different operating and meteorological conditions in Singapore. Based on the investigated effects from the feed and flashing temperature, the performance ratio and the relevant coefficient of performance were assessed. It was found that the performance ratio from the experiments varied from 0.77 to 1.15 and the system COP changes between 5.0 and 7.0. Al-Harahsheh [18] used a direct contact bubble column coupled with the heat pump subsystem to achieve the crystallization process. The theoretical analysis for the feasibility and the performance of the coupled system was focused on. Influences from the critical variables on the energy conservation performance was investigated. Based on the simulated results, great advantages were found compared to traditional open solar pond system, and energy saving potential was obtained compared to that of the ordinary process. Amin [19] built a pilot desalination system, mainly consisting of a direct expansion solar assisted heat pump, coupled to a single effect evaporator. The working fluid of R134a was used in the heat pump cycle, and distillate was produced through falling film evaporating and flashing processes. Based on the experiments in both day and night, the relevant influences from the meteorological conditions, solar irradiation and compressor speed were studied on the performance of the proposed system. It was found that the performance ratio acquired ranged from 0.43 to 0.88, and the average coefficient of performance and highest distillate production were reached 8 and 1.38 kg/h, respectively.

From the previous literature survey, it can be concluded that the heat pump integrated into the general desalination unit, such as single effect and multi-effect evaporation, have been investigated to enhance the corresponding desalination performance. However, the combination between the HDH desalination and heat pump unit, which are both prominent in energy conservation, is not involved, and it will be a novel idea to improve the energy utilization situation during the desalination process. In the present paper, the HDH desalination system is coupled with a heat pump. The seawater is heated by the condensation of the refrigerant while the hot discharged brine is cooled through the evaporation of the refrigerant. The integration mechanisms between the desalination and heat pump unit are revealed, and the corresponding mathematical models based on the first thermodynamic law are established. Energy analysis of the coupled HDH desalination system is accomplished. Furthermore, the critical parameters, mainly containing the compression pressure ratio, pinch temperature difference of the condenser and the effectiveness both for the humidification and dehumidification, are calculated and presented. The research results provide significant references for the design and farther optimization of the HDH desalination system.

2. Description of the HDH desalination system coupled with a heat pump

The configurations of HDH desalination system, which is integrated with a heat pump system, are presented in Fig. 1. It is seen that the HDH desalination subsystem mainly consist of the direct contact humidifier, surface dehumidifier, the heater or cooler while the heat pump subsystem is constituted of the condenser, valve, compressor and the evaporator. Obviously, according to the integration relationship, the condenser is also laid to heat the seawater and the evaporator is considered to recover the energy of the hot brine. Furthermore, a heater or cooler should be installed to heat the seawater or remove the extra released energy of the refrigerant in the condenser for the spraying temperature.

In the HDH desalination subsystem, the initial seawater flows into the dehumidifier, absorbing the latent heat during the condensing of the steam carried by the humid air. As a result, the hot humid air is cooled, with freshwater coming out from the bottom of the dehumidifier, while the seawater is preheated. Afterwards, the cooled humid air