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Experimental study of a humidification-dehumidification desalination system with heat pump unit

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ABSTRACT

In this paper, the performance of a humidification-dehumidification (HDH) desalination system with heat pump unit is experimentally investigated. The newly developed HDH system is comprised of humidifier, heat pump unit, 1st stage dehumidifier, plate heat exchanger and 2nd stage dehumidifier. The proposed system takes advantages of heat pump unit, which transfers heat to the seawater through the plate heat exchanger and absorbs heat from air through the 2nd stage dehumidifier in the meantime. Fresh water is accumulated from both the 1st stage dehumidifier and 2nd stage dehumidifier and the productivity of the proposed system is acceptable compared with other reported HDH systems and unaffected by solar radiation. The effects of seawater temperature, air temperature and air flow rate on system productivity are investigated. Seawater temperature has a positive influence on the productivity, while the effect of air temperature is insignificant. As the air flow rate increases, the productivity increases to the maximum value at a certain air flow rate and then decreases as the air flow rate still increases. The maximum productivity of the proposed system and the estimated cost of the fresh water are 22.26 kg/h and 0.051 USD/kg respectively, which are superior compared with other HDH systems.

1. Introduction

With the rising scale of industrial activity and growing population in many countries of the world, water demand has been increasing consistently. As an efficient way to produce water, desalination plays a vital role for regions where water resource is scarce. Traditional desalination methods are basically categorized to multistage flash (MSF), multiple effect distillation (MED), vapor compression (VC), solar stills, freezing, reverse osmosis (RO), electrodialysis (ED) and nanofiltration, which generally require substantial infrastructure and fossil fuels as the energy source. Nowadays, humidification-dehumidification (HDH) desalination technology is becoming a popular research hotspot because of its less occupied area, easier operability and greater compatibility with renewable energy [1]. For most of the HDH desalination plants, solar energy is utilized as the energy source to humidify the air in terms of environmental friendliness as well as energy and cost requirements [2,3].

It is notable that most reported HDH desalination plants are driven by solar energy. The relationship between fresh water productivity and solar radiation intensity for HDH desalination systems have been explored by many researchers. It is very apparent that higher solar radiation intensity results in greater productivity according to the investigations conducted by Orfi et al. [4], Elminshawy et al. [5] as well as Behnam and Shafii [6]. Thus it can be further asserted that the performance of solar HDH system declines dramatically under poor solar radiation conditions. Therefore, heat pump system, which can supply heating and cooling simultaneously, is introduced to replace the solar energy devices.

Heat pump technology has already been widely incorporated with traditional desalination technologies. Thermal flashing desalters were combined with a compression heat pump system by Slesarenko [7] and the thermodynamic analysis showed that the cost for fresh water was reduced substantially. Hidouri et al. [8] experimentally studied a hybrid system of a solar still connected to a heat pump and concluded that the daily fresh water productivity was enhanced from 2 L/m^2 for the simple system to 12 L/m^2 for the hybrid system while the average efficiency was enhanced from 20% to 80%. Halima et al. [9] established a mathematical model of a simple solar still coupled with heat pump

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Nomenclature

a	Accuracy
C	Cost, USD
E_B	Bias error
E_R	Random error
h_{fg}	Latent heat of vaporization, kJ/kg
i	Interest rate, %
m_{fw}	Fresh water productivity, kg/h
n	Lifetime, year
P	Electricity power, kW
Q	Heat transfer rate, kW
u	Uncertainty
X	Specific humidity, kg_w/kg_a

Greek

ε	Effectiveness
η	Efficiency
τ	Time, h

Subscript

$a1$	Air at humidifier inlet
$a2$	Air at 1st stage dehumidifier inlet
$a3$	Air at 2nd stage dehumidifier inlet
$a4$	Air at 2nd stage dehumidifier outlet
act	Actual
chp	Chilled water circulating pump
cp	Cooling water circulating pump
ele	Electricity
fa	Fan
fw	Fresh water
hp	Heat pump unit
hum	Humidifier
max	Maximum
sat	Saturation
$w1$	Seawater at 1st stage dehumidifier inlet
$w2$	Seawater at plate heat exchanger inlet
$w3$	Seawater at humidifier inlet
wp	Seawater pump

Abbreviation

AC	Annual cost
AMC	Annual maintenance cost
ARC	Annual running cost
ASV	Annual salvage value
CRF	Capital recovery factor
ED	Electrodialysis
F	Total fixed cost
FAC	First annual cost
GOR	Gained output ratio
HDH	Humidification-dehumidification
MED	Multiple effect distillation
MSF	Multistage flash
OPC	Overall performance coefficient
PID	Proportion integration differentiation
RO	Reverse osmosis
S	Salvage value
SFF	Sinking fund factor
USD	USA dollar
VC	Vapor compression

based on mass and heat balance. The fresh water productivity of the solar still with heat pump was found to be 75% higher than that of the conventional solar still. Li et al. [10] evaluated the feasibility of a hybrid multiple effect distillation system with absorption heat pump. The newly developed system was proved to be competitive compared with the reverse-osmosis technology. Alelyani et al. [11] numerically pioneered the combination of multi-effect distillation and ammonia-water absorption refrigeration systems. Predictions of cooling capacity and hourly water production, exergy analysis and cost estimation were conducted through a numerical model. Exergy and exergoeconomic for a hybrid multi-effect evaporation-absorption heat pump desalination system were evaluated by Esfahani et al. [12], in which the overall avoidable exergy destruction and overall avoidable cost rate were presented as two new evaluation indexes. Parham et al. [13] explored water purification systems with three categories of absorption heat pumps through a simulation model. The optimized maximum fresh water outputs of single, double and triple absorption heat transformer were calculated through the model.

The combination of HDH system and heat pump unit can be seen in few literatures. Yuan et al. [14] constructed an integrative device of air-conditioning and desalination, which was driven by mechanical vapor compression heat pump. The high primary energy ratio was obtained with the utilization of heat pump and pre-cooling exchanger. Gao et al. [15] manufactured a desalination unit driven by mechanical vapor compression pump, which was capable of producing 60 kg freshwater per day. Nada et al. [16,17], Elattar et al. [18] and Fouda et al. [19] executed a series of experimental and numerical investigations of a hybrid HDH desalination and air conditioning system, which was applied for both fresh water production and cold air supply. Effects of several operating parameters on system performance were assessed. Numerical correlations for fresh water production, cooling capacity and overall system energy consumption were presented in terms of various operating parameters within acceptable error. The integration of the hybrid system with solar collectors was also discussed.

A novel HDH desalination system with heat pump unit is developed in this study. Compared with the other reported HDH desalination system, the heat released by the condenser and cold released by the evaporator are adequately used. Furthermore, to promote the heat and mass transfer in the humidifier, counterflow packing material is introduced to the proposed system. With the improvements, the maximum productivity, humidifier efficiency, dehumidifier effectiveness, overall performance coefficient and economic cost of fresh water are all studied and compared with the other HDH systems. Effects of seawater temperature, air temperature and air flow rate on the system productivity are also experimentally investigated and analyzed. This research provides a promising approach which can promote HDH desalination technology in the areas where solar energy is deficient.

2. Experimental setup and procedure

Fig. 1 illustrates a principle schematic of the proposed system and Fig. 2 is the phototype of the proposed experimental setup after the insulation is installed. The HDH desalination system with heat pump unit in this research contains humidifier, heat pump unit, 1st stage dehumidifier, plate heat exchanger and 2nd stage dehumidifier. The proposed system consists of five loops including air loop, seawater loop, refrigerant loop, cooling water loop and chilled water loop.

As shown in Fig. 1, air is circulating in an open loop and withdrawn from the ambient to the humidifier by fan. Heat and mass transfer between the hot seawater and air in the humidifier contributes to high humidity ratio of the air at humidifier outlet. The air from the humidifier is transported toward the 1st stage dehumidifier and 2nd stage