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Humidification-dehumidification desalination system operated by a heat pump

Dahiru Lawal[a], Mohammed Antar[a,b,*], Atia Khalifa[a], Syed Zubair[a,b], Fahad Al-Sulaiman[a,c]

[a] Mechanical Engineering Department, KFUPM, Saudi Arabia
[b] Center of Research Excellence for Water Desalination at KFUPM, Saudi Arabia
[c] Center of Research Excellence for Renewable Energy, Saudi Arabia

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ABSTRACT

Humidification-dehumidification is a carrier gas based thermal technique that is ideal for small-scale water desalination applications. One advantage of humidification-dehumidification systems is the ability to utilize low grade and renewable energies as heat source to drive the system. This work presents theoretical investigation of humidification-dehumidification desalination system operated by a heat pump. The model is based on the first law of thermodynamics, describing heat and mass transfer in the combined humidification-dehumidification-heat pump cycle. The model predicts the performance of closed-air open-water water-heated, and modified air-heated cycle coupled with a heat pump. To improve the Gain output ratio and energy recovery of the system, a heat pump is used as the source of heating and cooling for the humidification-dehumidification desalination system. Energy rejected in the condenser is used as a source of heat in the humidifier whereas the cooling effect of the evaporator is used to cool incoming seawater for effective condensation of humid air in the dehumidifier. A parametric study is conducted to investigate the influence of system operating parameters, including water and air flowrate, seawater temperature, and refrigerant flow rate on the system performance. Results indicate a maximum Gain output ratio of 8.88 and 7.63 obtained at 80% components effectiveness and mass flow rate ratio of 0.63 and 1.3 for modified air heated and water heated cycle, respectively. A maximum gain output ratio greater than 10 can be achieved for humidifier and dehumidifier effectiveness of 100% leading to more energy efficient systems. The cost of desalinated water production is calculated and the effect of major parameters on its variation is also presented.

1. Introduction

Fresh water scarcity is among the main problems faced by many societies, and it is a global issue along with the challenge undergoing accelerated urbanization, rapid population and economic growth. The shortage of fresh water is a matter of high concern as most of the world population suffers from clean water shortage. One potential solution to tackle this issue is to develop reliable, efficient and cost effective decentralized small-scale water desalination systems to make the clean water accessible for most of the world population. Several desalination technology have been developed in the past. The oldest and economical method to obtain clean water is from solar stills. Although this method is not very efficient but it has been the central focus of many researchers due to its simplicity, portability and economic advantages. A lot of work has been done to develop new technologies for small-scale water desalination and many prototypes were made to validate these new ideas. Although, these prototypes might not be the best choice to compete with the current conventional desalination approaches, but prove useful to develop reliable, efficient and cost effective decentralized small-scale water desalination systems.

Humidification-dehumidification (HDH) desalination system is a carrier-gas based thermal technique that can be used for small-scale water desalination systems [1]. Some silent features of HDH system includes the use of low-grade energy, simplicity in its design and ease of manufacturing. It is especially suited for decentralized and small-scale water desalination in arid regions [2]. The basic components of HDH system include a humidifier, a dehumidifier, a water or air heater, pumps and piping. Various designs formed with different components and cycles have been proposed and analyzed by researchers. Several studies that explore HDH as an effective means for seawater desalination are available in the literature. Some of the early work on HDH system is reported in [3] where waste heat from a gas turbine power plant has been used for the system. Abdel-Salam et al. [4] designed, constructed, and tested a test rig of air humidification-

* Corresponding author at: Center of Research Excellence for Water Desalination at KFUPM, Saudi Arabia.
E-mail address: antar@kfupm.edu.sa (M. Antar).

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Nomenclature

Acronyms

HDH	humidification-dehumidification
HP	heat pump
GOR	gain output ratio
CAOW	closed air open water
RR	recovery ratio (%)
MR	mass flowrate ratio
sW	specific work consumption (kj/kg)

Symbols

C_F	annual capital cost
C_T	total annual cost
C_P	unit product cost
COE	cost of energy (unit cost of electricity)
EPC	annual electric power cost
f	plant availability
h	enthalpy (kj/kg)
h_{fg}	latent heat of vaporization (kJ/kg)
i	interest rate
$\mathscr{L}$	specific cost of operating labor
L_c	annual labor cost
n	amortization years (life of the system)
P	pressure (kpa)
T	temperature (k)
$\dot{m}$	mass flow rate (kg/s)
Cp	specific heat capacity at constant pressure (kJ/kg K)
$\dot{Q}$	heat transfer rate (kW)
SW	specific work

Greek letters

α	amortization charges (capital recovery factor (CRF))
ε	effectiveness
ω	humidity ratio

Subscripts

a	air
b	brine
W, sw	water
fw	fresh water
in	entering/output
out	intput/exiting
r	refrigerant
1, 2, 3, …	state points
Evap	evaporator
Comp	compressor
cond	condenser

dehumidification. They developed a computer programs to correlate the experimental data using multi-regression and variance techniques. They found out that among other factors, the inlet water temperature to the humidifier has the most significant positive effect on the productivity of the system and recovery ratio. Performance of solar desalination using humidification-dehumidification cycle has been investigated in [5]. They constructed two units of different sizes from different materials. The systems productivity was found to be much higher than those of the single-basin still. Multi-effect humidification (MEH) based on the evaporation and condensation of water inside a thermally insulated box at ambient pressure, originally developed at the at the University of Munich has been optimized by The Bavarian Center of Applied Energy Research (ZAE Bayern) and T.A.S. GmbH & Co. KG, Munich [6]. The principle of functioning and the characteristics of humidification and dehumidification technique is presented [7]. The state of the art regarding the humidification and dehumidification technique was equally presented in the paper. Xiong et al. [8] presented an experimental investigation of a baffled shell and tube desalination unit to perform humidification and dehumidification simultaneously at the tube and shell side of the column, respectively. Their system combined both humidifier and dehumidifier as a single unit instead of separate unit. Similar idea was used [9] for a vertical tubular desalination unit with shell and tube structure to perform humidification and dehumidification simultaneously on the tube and shell side of the column, respectively.

Significant research has been carried out to enhance the performance of HDH systems and one of the performance indicator of HDH system is the Gained-Output-Ratio (GOR). GOR is an important parameter, which was proposed to assess the performance of desalination system [10]. It is defined as the ratio of heat of evaporation of the water produced to the heat input to the system [11]. Antar and Sharqawy [12] experimentally investigated single and double-stage air-heated humidification-dehumidification desalination system (HDH), driven by evacuated tube solar heaters. Narayan et al. [11] carrieded out thermodynamic analysis of various HDH cycles, which was achieved by detailed theoretical analysis. Their results showed a GOR exceeding 5 for multi-stages HDH coupled with thermal vapor compression cycles. In order to increase the energy efficiency of HDH system, a HDH system combined with a reverse osmosis (RO) unit was proposed [13]. It was found that the GOR of the new system could reach up to 20, which is much higher than the GOR of other existing HDH systems. Siddiqui et al. [14] presented a HDH system that works at different pressures. They reported a maximum GOR of 8.2 for a system operating at a humidifier pressure of 50 kPa, and 90% effectiveness at a pressure ratio of 1.33. Modification of various components of HDH system reported in [15] resulted in an improved productivity through saving of input energy to the system. In their work, an air heater was modified with inserts like short length taper twisted tape; internally finned cut out conical turbulator and half perforated circular inserts with various orientations and three different pitch ratios (PR). Gunny bag and saw dust was used as the humidifier, while the dehumidifier was integrated with spring inserts of different PR to enhance its performance. They observed a noticeable saving in energy with significant development in energy and exergy efficiency. Ahmed et al. [16] improved the productivity of HDH system through the introduction of corrugated packing aluminum sheets in the humidifier. Condensate of as high as 15 kg/h was achieved in the study.

Investigations on the application of heat pump as source of energy for several desalination systems is ever increasing. Hawlader et al. [17] carried out an experiment on solar assisted heat pump desalination system. Single effect evaporation desalination unit was adopted in the study. The coefficient of performance (COP) and the performance ratio (PR) were evaluated from the experiment and were found to range from 5.0 to 7.0, and 0.77 to 1.15 respectively. Gude and Nirmalakhandan [18] presented and analyzed combined desalination and solar-assisted air-conditioning system. They also presented model and performance curves of the proposed combined system. Their results indicated that the rejected thermal energy by absorption refrigeration system (ARS) of about 3.25 kW combined with an additional energy input of 208 kJ/kg of desalinated water is sufficient to produce desalinated water at an average rate of 4.5 kg/h. This is reported to be competitive with that of the multi-stage flash distillation (MSF) process operating at the same capacity (338 kJ/kg). Their model predictions showed that the proposed system could reach a desalination efficiency of 80–90%.