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Performance analysis of proposed hybrid air conditioning and humidification–dehumidification systems for energy saving and water production in hot and dry climatic regions

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ABSTRACT

Performance of integrative air-conditioning (A/C) and humidification–dehumidification desalination systems proposed for hot and dry climatic regions is theoretically investigated. The proposed systems aim to energy saving and systems utilization in fresh water production. Four systems with evaporative cooler and heat recovery units located at different locations are proposed, analyzed and evaluated at different operating parameters (fresh air ratio, supply air temperature and outside air wet bulb temperature). Other two basic systems are used as reference systems in proposed systems assessment. Fresh water production rate, A/C cooling capacity, A/C electrical power consumption, saving in power consumptions and total cost saving (TCS) parameters are used for systems evaluations and comparisons. The results show that (i) the fresh water production rates of the proposed systems increase with increasing fresh air ratio, supply air temperature and outdoor wet bulb temperature, (ii) powers saving of the proposed systems increase with increasing fresh air ratio and supply air temperature and decreasing of the outdoor air wet bulb temperature, (iii) locating the evaporative cooling after the fresh air mixing remarkably increases water production rate, and (vi) incorporating heat recovery in the air conditioning systems with evaporative cooling may adversely affect both of the water production rate and the total cost saving of the system. Comparison study has been presented to identify systems configurations that have the highest fresh water production rate, highest power saving and highest total cost saving. Numerical correlations for fresh water production rate and total system energy consumption are developed and presented in terms of the controlling parameters.

1. Introduction

World population growth and the increase of industrial and human activities have led to excessive needs of air conditioning and potable/drinkable water, especially in hot and dry climatic regions. Recently, hybrid air conditioning and water desalination systems using humidification–dehumidification technique driven by mechanical vapor compression (MVC) are used for energy saving. MVC desalination was one of the most efficient thermal distillation processes for its compactness and suitability for small and large potable unit. Faisal et al. [1] developed mathematical models and performed a comparison for four different types of single-effect evaporator desalination systems (thermal, mechanical, absorption, and adsorption vapor compression heat pumps). Siqueiros and Holland [2] carried out a review of the experimental works on water purification driven by heat pump. Slesarenko [3] suggested incorporating heat pumps as a source of heat energy for seawater desalination plants. Two plants were proposed; one operated with compression heat pump using R12 and the other operated with steam and water cycle. Al-Ansari et al. [4] modeled and analyzed a single effect evaporation desalination process combined with adsorption heat pump (ADVC) in terms of designed and operational system parameters. Aly et al. [5] described and studied theoretically and experimentally the performance of the mechanical vapor compression (MVC) desalination system. Hawlader et al. [6] described a novel solar assisted heat pump desalination system. The effects of feed water temperature and flashing have been investigated. The study revealed that a good fresh water production rate can be obtained from the system. Heat pumps using agent R12 or water and vapor to be used as a source of heat energy for seawater desalination were introduced by Jinzeng and Huang [7].

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Nomenclature

$\dot{E}$	total electric power, kW
TCS	total cost saving
h_{fg}	latent heat of evaporation of water, kJ/kg
i	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
$\dot{m}_{steam}$	steam mass flow rate, kg/s
$\dot{Q}$	refrigeration capacity, kW
R	water system recovery
RSHF	room sensible heat factor
T	temperature, °C
TR	Tone of refrigeration
W	air specific humidity, $kg_{water}/kg_{dry\ air}$
$\dot{W}_c$	compressor power, kW
Greek symbols	
η_h	humidifier efficiency
ε	effectiveness of heat recovery
Subscript	
A	air
BS	basic systems
Cc	cooling coil
Db	dry bulb
E	evaporator
evc	evaporative cooler
feed	feed water
H	humidifier
I	inlet
Min	minimum
Max	maximum
O	outlet
R	room
RH	relative humidity
PS	proposed systems
S	conditioned space supply state
W	water
Wb	wet bulb

Yuan et al. [8] presented an integrative unit for air-conditioning and desalination driven by vapor compression heat pump on basis of direct humidification–dehumidification process. The performance of a new type of a humidification–dehumidification desalination unit driven by mechanical vapor compression heat pump using mathematical model to study the flow and heat and mass transfer inside the humidifier was analyzed by Gao et al. [9]. Wu et al. [10] analyzed theoretically the heat and mass transfer between air and water film in the direct evaporative cooler. An open air–vapor compression refrigeration system for both air-conditioning and desalination on ship cooled by seawater was presented by Houa et al. [11]. The heat and mass transfer between water and air in a direct evaporative cooler was developed by Wu et al. [12] using numerical model with treating the mass of evaporated water as a mass source of air flow, and the latent heat of water evaporation as a heat source in the energy equation. Performance study of a combined heat pump (HP) with a dehumidification process to produce fresh water from the atmospheric air was analyzed by Habeebullah [13]. Nada et al. [14] experimentally investigated the performance of a hybrid humidification–dehumidification water desalination and air conditioning system using vapor compression refrigeration cycle. Attia [15] introduced a new proposed system for freeze water desalination using auto reversed R-22 vapor compression heat pump, the system depends on optimization of utilizing the heat flow of the heat pump system to increase the whole system efficiency. Rane and Padiya [16] discussed a patented layer freezing based technology which was scalable and coupled with a heat pump to switch freezes water from seawater in the evaporator and melts the ice in the subsequent phase when it serves as a condenser. Jain and Hindoliya [17] presented performance analysis of two new evaporative cooling pad materials namely coconut fibers and palash fibers and compared with that of aspen and khus pads which are commonly made now-a-days. Malli et al. [18] studied experimentally the thermal performance of two types of cellulosic evaporative cooling pads which were made from corrugated papers. Mehrgoo, and Amidpour [19] used the constructal theory for conceptual design of a humidification dehumidification (HD) desalination unit and they showed that the main design features of a direct contact HD desalination process can be determined based on the method of the constructal design. Shatat et al. [20] developed a mathematical model to describe the affordable small scale solar water desalination plant using the psychometric humidification and dehumidification process coupled with an evacuated tube solar collector.

Performance limits of zero and single extraction humidification–dehumidification desalination systems was investigated theoretically by McGovern et al. [21]. The investigation was done by considering heat and mass exchangers to be sufficiently large to provide zero pinch point temperature and concentration differences within the humidifier and dehumidifier. Shen et al. [22] presented a comprehensive analysis of a single-effect of mechanical vapor compression (MVC) desalination system using water injected twin screw compressors. The operational characteristics of the twin screw compressor including inlet volume flow rate, compressor pressure ratio, and mass fraction of injected water were investigated. Theoretical study of a simple solar still coupled to a compression heat pump using mass and heat balance was presented by Halima et al. [23].

Kang et al. [24] developed a mathematical model to investigate the performance of a two-stage multi-effect desalination system based on humidification–dehumidification process with variation of the control parameters. Younes et al. [25] presented new humidification–dehumidification process desalination technology named "Humidification Compression (HC)" which has some advantages (such as: high energy performance, high recovery flow rate, energy recovery) in comparison with other similar methods. Aybar [26] presented mathematical modeling to study the operation characteristics of a low-temperature mechanical vapor compression desalination system. The compressor work and the mass flow rate of the distilled water were investigated against the evaporation side pressure, the condensation side pressure, and the water inlet temperature. Zhang et al. [27] proposed a novel air dehumidification system, namely, mechanical dehumidification with membrane-based total heat exchanger using thermodynamic modeling. The annual primary energy consumptions for the system through hour-by-hour analysis was presented and discussed. Bahar et al. [28] performed experimental work on a mechanical vapor compression desalination system (MVC). The performance of the system was evaluated under different values of brine recirculation rate and compressor speed. Ettouney et al. [29] proposed