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Solar assisted modified variable pressure humidification-dehumidification desalination system

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ABSTRACT

Variable pressure humidification technology is proposed for seawater desalination through evaporation at pressure(s) less than atmospheric and subsequent condensation. Two sub-atmospheric humidification processes (process-I and II) utilizing solar heat are proposed and assessed theoretically. The desalinated water production rate, gained output ratio and an economical comparison between processes are made subject to similar operating conditions. It is deduced that, under similar conditions, pressure reduction from 0.9 bara to 0.1 bara leads to approximately 50% increase in the desalinated water production rate in each of the proposed processes. For humidifier pressures less than atmospheric pressure, the maximum gained output ratio for process-II is higher by 139.13% than that of process-I while the distilled water production rate is lower by 5.71%. Unlike other variable pressure desalination processes, there is no need to use compressor when the vacuum pump is present. To have a comprehensive study of the proposed systems and determine their feasibilities, a cost analysis is conducted. The result of cost analysis indicates that the total cost per liter of distilled water in two proposed process are 0.034 and 0.041 US $/L, respectively. This value is estimated to be reduced to 0.002 US $/L for an industrial scale variable pressure humidification-dehumidification plant.

1. Introduction

In many arid, semi-arid or remote areas of the world such as coastal areas, especially in the Middle East and some Mediterranean islands, the shortage of sweet water is becoming critical. With the increase in the world's population, together with industrial and agricultural activities, the scenario will worsen. Desalination is an industrial process that extracts fresh water from seawater. Desalination of seawater is usually performed based on two main processes: (a) by evaporation of saline water or (b) by applying a membrane to separate fresh water from a saline concentrate. The former applies a heat source for the desalination of seawater, while the latter applies electricity either for driving high-pressure pumps or for establishing electric fields to separate the ions.

In the conventional desalination processes, consuming fossil fuels can become more costly and have a negative effect on the environment. Moreover, the dependency on fossil fuel makes the conventional desalination techniques less applicable in decentralized water production. In order to overcome these drawbacks, new economical methods are introduced for the production of potable water at an acceptable cost by applying renewable energy sources, such as solar energy, ocean thermal energy, geothermal energy and waste heat produced from combustion engines. Abolfazli et al. [1] proposed using the thermoelectric cooler to increase temperature difference between evaporation and condensation chambers. Rahbar et al. [2] modified this system by adding heat-pipe cooling device in order to cool down the hot side of the thermoelectric cooler. The superiority of their system to the conventional desalination processes was the earlier start time of water production [3]. Among different desalination process, the conventional humidification dehumidification (HDH) desalination systems are more attractive due to their simplicity in design, operation at low temperature and their feasibility in solving fresh water shortages [4]. It should be noted that, in the conventional HDH desalination systems both humidifier and dehumidifier operate at atmospheric pressure.

Recently some attention is paid to the effect of pressure on the performance of desalination units by few researchers. By reducing the pressure of the system, the moist air humidity ratio (the ratio of water vapor mass to dry air mass) throughout the system increases. For example, at atmospheric pressure and a dry bulb temperature of 72 °C, the humidity ratio is about 1/4 of that at 50 kPa. This phenomenon would shed light on the scope for further studies and recommendations in active desalination process.

Solar still is a simple and economical method to separate fresh water from the seawater. The desalinated water production rate depends on

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Nomenclature

AC	Annual Costs (US$)
AMC	Annual Maintenance Costs (US$)
ARC	Annual Running Costs (US$)
ASV	Annual Salvage Value (US$)
AY	Annual Yield (L)
bara	pressure per absolute bar
CEPCI	Chemical Engineering Plant Cost Index
CRF	Capital Recovery Factor
Ey	total electricity consumption (kWh)
FAC	First Annual Cost (US$)
G	air mass flow rate ($kg \cdot s^{-1}$)
GOR	Gained Output Ratio
H	enthalpy ($kJ \cdot kg^{-1}$)
hfg	water latent heat of evaporation ($kJ \cdot kg^{-1}$)
HDH	humidification dehumidification
L	water mass flow rate ($kg \cdot s^{-1}$)
$\dot{m}$	mass flow rate ($kg \cdot s^{-1}$)
n	lifetime (year)
N	number of experimental measurements
$\dot{Q}$	energy produced in heater
S	salvage value (US$)
SFF	Sinking Fund Factor
P	initial fixed capital cost (US$)
$\dot{W}$	rate of work (W)
Z	electricity cost ($US\$ \cdot kWh^{-1}$)

Greek symbols

w	outlet humidity ratio of the humidifier (kg vapor/kg dry air)
ε	relative error

Subscripts

a	dry air
comp	compressor
exp	experimental
sim	simulation
vac,pump	vacuum pump

the solar still configuration, water depth, absorber material and color, operation condition and location. The solar still operating condition modification through vacuum process was developed by Gnanadason et al. [5]. The system performance for 3 cm water depth with and without vacuum condition was compared. In the proposed system, the performance of a basin under vacuum is higher by about 25% than the basin without vacuum. It was deduced that a decrease in still pressure leads to enhance the evaporation/condensation rates, hence higher performance. The fresh water productivity in a solar still for various sub-atmospheric pressures and materials of absorber was evaluated by Sriram et al. [6]. A comparison between a low pressure still and an atmospheric pressure still was made. In vacuum condition and the case of light black cotton cloth as absorber, an increase in the performance by 88.66% is obtained. A major negative aspect of the solar still is the energy loss in the form of latent heat of condensation [7]. In order to solve this problem, HDH principle has been established [8].

Gravity assisted vacuum desalination HDH system was proposed by Elshargawy et al. [9]. In proposed system, humidification and dehumidification chambers were each operated at sub-atmospheric pressures attained by a static head. The system consisted of a humidifier and a dehumidifier at an equal height with about 10 m standpipes. The concept of the hydrostatic and atmospheric pressures balancing to create the vacuum in both chambers was used. Seawater levels at the tanks' surface at the bottom of the standpipes can produce a Torricellian vacuum inside the chambers. Although this system is not portable, creating the vacuum does not need any energy input, therefore, less energy consumption. By comparison the obtained gained output ratio (GOR) for atmospheric and sub-atmospheric operating condition, higher GOR in sub-atmospheric pressure was obtained. In this study, about 30% improvement in GOR when the pressure changes from 1 bar to 0.3 bar was deduced, hence, sub-atmospheric pressure desalination will prove to be more efficient than atmospheric pressure. The desalinated water production rate of the HDH system was improved by directing a carrier gas through a fluid flow pathway in a humidifier and the dehumidifier operating at a sub-atmospheric pressure by Elsharqawy's desalination group in another assessment. In multi-extracted HDH system which air was extracted from an individual intermediate position in the humidifier and fed to corresponding individual intermediate position in the dehumidifier the GOR increased to higher values. This system can be extended for separation of a vaporizable component in HDH system subject to operation of both humidifier and dehumidifier at sub-atmospheric pressure [10].

Performance enhancement of the HDH system could be resulted if the process run under variable pressure. In these processes the humidifier and the dehumidifier work at sub-atmospheric and over-atmospheric pressures, respectively. Sub-atmospheric pressures can be provided via a vacuum pump/liquid ejector or static head and over-atmospheric pressures can be provided via a compressor. It was reported that if the entire HDH system run subject to a reduced pressure, no significant increase in GOR would be resulted. This drawback has been solved by the variable pressure HDH systems [11]. Also, from the investigations reported for the cycles studied by Narayan et al. [12], it was deduced that the exit humidity from the dehumidifier was higher than that of the atmospheric pressure case. They proposed a modified air heated sub-atmospheric HDH cycle, in which an increase in performance by about 30% was deduced. Fixed-effectiveness[1] of 80% for humidifier and dehumidifier was considered. In this operating conditions the capacity of the moist air to carry vapor in the humidifier and the condensation of the vapor in the dehumidifier increased, and as a result, the desalinated water production rate and the GOR of the HDH system improved. In a theoretical investigation that conducted by Narayan et al. [13] the variable pressure condition was achieved via a compressor. A throttle valve was used as an expander. They calculated the specific work consumption via the devices in their system and reported that using the throttle valve imposes more irreversibility in system than other devices.

A HDH desalination system consisted of bubble column humidifier and dehumidifier in variable pressure was studied by Elsharqawy and Liu [14]. The performance was assessed through determining the effectiveness and the heat transfer rate. Through the operating at sub-atmospheric pressure condition in the humidifier, the improvement in the heat transfer by 35% and the effectiveness by 7.1% was deduced. However, through the operating at over-atmospheric pressures in the dehumidifier, a heat transfer rate enhancement by 27% was obtained but effectiveness was reduced by 3.2%. It was also resulted that liquid height in the column has no significant effect on the performance. In this study the mass transfer coefficient as a function of the superficial velocity and pressure was revealed.

A performance of variable pressure HC desalination was assessed experimentally and theoretically by Ghalavand et al. [15,16]. In this process, air was humidified through direct contact with hot water in a

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[1] The ratio of actual enthalpy change of either stream to maximum possible enthalpy change