Desalination 437 (2018) 81–88

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Experimental investigation of heat recovery in a humidification-dehumidification desalination system via a heat pump

Mohammad Behshad Shafii[a,*], Hamed Jafargholi[b], Meysam Faegh[a]

[a] Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran
[b] Sharif Energy Research Institute (SERI), Tehran, Iran

ARTICLE INFO

Keywords:
Desalination
Humidification-dehumidification (HDH)
Heat pump

ABSTRACT

A hybrid HDH desalination system integrated with a heat pump was experimentally studied. In this system, heat pump's heating was used to raise the temperature of the air entering the humidifier and its cooling effect was used for dehumidification of humid air and freshwater production. In other words, heat pump's condenser works as the heater of the HDH cycle and its evaporator works as the coolant for the dehumidifier of HDH cycle. The effects of different parameters such as mass flow rate of inlet saline water (relative humidity of the air passing the dehumidification section), volume flow rate of the air passing the dehumidification section and ambient air temperature on freshwater production and GOR were investigated. Analyzing the experimental results indicated that the highest yield and GOR reaches 2.79 kg/h and 2.08, respectively. It was also observed that increasing the relative humidity and volume flow rate of the air passing the dehumidification section results in higher GOR values for the system. Additionally, it was seen that raising the ambient temperature leads to a reduction in the system's GOR. The economic analysis showed that the CPL of the current study is 0.0114 $/L.

1. Introduction

As the world population increases and energy crisis intensifies, supplying freshwater by consuming the minimum amount of energy has become one of the most important challenges in the world. For decentralized water production, due to the lack of infrastructures and economic resources and also the far distance from large-scale plants, existing desalination technologies such as reverse osmosis (RO), multi-stage flash (MSF) and multi-effect distillation (MED) might not be suitable [1]. Therefore, in the small scales (5 to 100 m^3 daily yield), using methods such as RO might not be cost effective and requires experts to be able to utilize these systems [2]. In comparison with other desalination methods, the humidification-dehumidification method has a number of advantages such as simple design, flexibility, low maintenance and capital cost, long lifetime (over twenty years), utilization of low-grade energy, operation at atmospheric pressure, applicability in rural areas for supplying the freshwater needed for agriculture and drinking [3–5].

The HDH method resembles the natural water cycle and solar stills are known as its simplest form. Reviews on a number of most recent works on solar stills can be found in [6–8]. Due to the fact that the heat and mass transfer processes (solar energy absorption, evaporation, and distillation) occur in a unit chamber and also due to the loss of latent heat of condensation, solar stills have low performance (GOR < 0.5). The basis of the HDH method is the separation of these processes and recovery of the latent heat of condensation and thereby improving system performance. In the simplest case, an HDH system has 3 sections, namely air/water heater, humidifier, and dehumidifier. Depending on the arrangement of these sections, different cycles can be obtained. Two of the most important HDH cycles are closed air open water (CAOW) and open air open water (OAOW). In addition, the selection of heater type is among the most important points to consider for HDH systems. Mistry et al. [9] studied the numerical optimization of CAOW and OAOW systems with air/water heaters and obtained the optimum performance in order to increase GOR for the all the cycles under study. Results indicated the variability of each cycle's (OAOW, CAOW, etc.) superiority in different working conditions. Dai and Zhang [10] experimentally studied a HDH system and used a solar collector to heat the saline water before spraying. It was seen that the temperature and mass flow rate of the inlet saline water and also air flow rate all have a great impact on water production rate. According to previous studies, air heating is generally preferred over water heating due to its simplicity, flexibility and being cost effective [11]. Yanniotis and Xerodemas [12] studied the performance of tubular spray and pad humidifiers in an HDH system both numerically and experimentally. Investigating the effects of temperature and flow rate of inlet air and

* Corresponding author.
E-mail address: behshad@sharif.edu (M.B. Shafii).

https://doi.org/10.1016/j.desal.2018.03.004
Received 9 November 2017; Received in revised form 4 March 2018; Accepted 4 March 2018

Nomenclature

A	area (m^2)
c_p	specific heat (kJ/kgK)
GOR	the gained output ratio
h	enthalpy (kJ/kgK)
L	latent heat of vaporization (J/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	the rate of heat transfer (kW)
R	ideal gas constant (kJ/kgK)
T	temperature (°C)
V	velocity (m/s)
$\dot{V}$	volumetric flow rate (m^3/h)
W_c	compressor power (w)

Greek letters

ϑ	specific volume (m^3/kg)
$\varnothing$	relative humidity (%)
ω	moisture content of air (kg_{water}/kg_{air})

Subscripts

1	condenser inlet
2	condenser outlet
3	evaporator inlet
4	evaporator outlet
5	ambient
6	fresh water outlet
7	humidifier outlet
a	air
f	saturated liquid state
g	saturated vapor state
w	water

saline water showed the superiority of pad humidifiers from the water production standpoint. Al-Enezi et al. [13] studied the operating conditions of an HDH system experimentally. The system consisted of a packed humidification column and its dehumidifier was cooled by a secondary water flow. It was seen that higher air flow rates and lower cooling water temperatures lead to more yield.

In addition to the studies conducted with the goal of improving the main components of HDH systems, one of the most important design challenges is decreasing consumed energy by using it more effective in the various sections of the system. Heat pumps are suitable devices to couple with desalination systems. A review of the literature on combining heat pumps and desalination systems can be seen in [14]. Some researchers have studied the benefits of using cooling effect of heat pumps in HDH cycles. Chiranjeevi and Srinivas [15,16] experimentally and thermodynamically analyzed the advantages of using the cooling effect of an absorption heat pump in a two-stage HDH desalination system. Dehumidification in this system was done by two air-cooled dehumidifiers and in the last stage, the cooling effect of an absorption heat pump was used for further dehumidification. The results indicated that increasing the flow rate and temperature of the inlet saline water in the humidifier leads to higher yield. Marale et al. [17] performed an experimental and numerical modeling study on the humidifier of a hybrid two-stage HDH desalination system utilizing cooling effect from an absorption heat pump. Their findings led to a model for verification of a humidifier unit's performance based on experimental results. Moreover, the numerical modeling part of their work makes possible the calculation of optimum humidification parameters for different geometrical and operational conditions. Nada et al. [18] experimentally investigated an HDH hybrid system and heat pump. The heat pump is used for air dehumidification and the desired indoor air is provided by distilling freshwater. It was concluded that increasing the air's absolute humidity and mass flow rate leads to higher yield, cooling capacity, and specific compressor work. Completing this work, Elattar et al. [19] did a parametric and economic study on a solar hybrid air conditioning and HDH desalination system from a thermodynamic standpoint. In this system, flat plate collectors and auxiliary heaters were used for heating water and air. Additionally, cooling effect from a heat pump was used for air dehumidification, production of freshwater and supply of desired air for domestic purposes. Results showed that as the outside air flow rate is reduced, the auxiliary heater consumes less electric energy. Moreover, higher outside temperature and humidity lead to increase in water yield, recovery rate, cooling capacity and consumed electric energy. Economic analyses indicate that as outside temperature and humidity increase, a drop can be seen in operational costs. Theoretical analysis of the performance of hybrid air conditioning and HDH systems was performed for energy saving purposes [20]. In this system, dehumidification of humid air was done by the cooling effect of a heat pump and alongside freshwater production, the air was also provided for the house. The effect of the existence or absence of recovery heat exchanger and air mixing before and after the humidifier was studied. It was seen that energy saving and water production increased with inlet air temperature. Furthermore, the optimum value of the inlet fresh air flow rate was obtained to minimize consumed energy.

Using heat pumps as the heat source in HDH cycles has also been the subject of a number of studies [21,22]. Franchini et al. [21] modeled the utilization the heat loss from the absorption heat pump as the inlet heat source for the HDH system. This process results in improving system performance, due to the low Coefficient of performance of the absorption cycle. At low water temperatures, chiller capacity and heat transfer to the HDH system increase and also the desalination process is improved. Additionally, decreasing water flow rate leads to a reduction of input heat to the HDH system and consequently product water. Recently, Sahoo et al. [22] did a thermodynamic study on polygeneration of power, cooling, and desalination system. Solar and biomass energy sources were used to run the power cycle. A portion of turbine's steam was used as a heat source in the absorption cooling cycle and the released heat in the cooling cycle was used as the heat source in the HDH desalination system. It was seen that system's energy consumption dropped by 50.5%.

Simultaneous supplying the heating and cooling effect required for the HDH system by a heat pump has great significance from an energy recovery standpoint. Yuan et al. [23] performed an experimental study in which they investigated the use of a heat pump heating as the heat source for the HDH cycle and its cooling effect for air dehumidification and freshwater production. In their study, air is heated by a condenser of the heat pump and moves towards the humidifier. The exiting air from the humidifier initially goes through an air-cooled heat exchanger and enters the heat pump's evaporator which leads to freshwater production using the cooling effect it provides. It should be noted that another auxiliary heat exchanger is placed in the system for heating the input saline water. Effects of flow rate and inlet saline water temperature and humidifier length were studied. Results indicated that water yield increases with increasing the temperature and water flow rate. Gao et al. [24] numerically and experimentally analyzed a desalination HDH system which used heating and cooling effect from a heat pump. In this system, air flows in a closed loop, preheated in a flat plate collector, heated by a heat pump condenser and enters the humidification section. Air is cooled by the heat pump's evaporator at the