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Mathematical modeling for humidifier performance in a compression desalination system: Insulation effects

Younes Ghalavand*, Amir Rahimi, Mohammad Sadegh Hatamipour

Chemical Engineering Department, University of Isfahan, Isfahan, Islamic Republic of Iran

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A B S T R A C T

The performance of humidifier was studied in a solar humidification-dehumidification desalination in which dehumidification is carried out by compression. The modified mathematical models were developed to investigate the effect of operating condition on humidifier performance. The modeling results were evaluated by experimental data and compared with those of another mathematical modeling. The results showed, in the mathematical model with insulation effect the model precision increases compared to the model without insulation effect and the absolute error is decreased up to 2.4% based on experimental data.

1. Introduction

The growth in world population accompanied with an increase in industrial and agricultural activity has resulted in the pollution of fresh water resources. Thus, is necessary to apply different and advanced methods to convert polluted water or saline water into usable or drinking water. One flexible thermal desalination method is humidification of a carrier gas [1]. There are three main techniques for desalination by carrier gas: humidification dehumidification (HDH) [2], humidification compression (HC) [3] and dew-vaporation [4]. These methods can be used in remote or arid areas to supply potable or drinking water. Since many parameters such as climatic conditions can affect the system performance, many researchers have focused on modeling these systems with considering operating and climatic conditions through the experimental and theoretical investigation.

A 3-stage multi-effect solar HDH desalination process was assessed experimentally by Gang et al. [5]. In their study, different effects of heating methods on the high and middle stages of the desalination unit (i.e., inlet feed temperature, airflow rate, condenser drainage, and the supplement water flow rates) were examined. Results showed that the maximum yield of the unit (0.182 m3/h) could be reached in the maximum GOR (Gain Output Ratio) of about 2.65 in their studied setup. Also, the results indicated that desalinated water production of the system decreases with the increase in the supplement water flow rate and condenser drainage. Water production cost was calculated about $2.5 per ton. Performance evaluation of an HDH desalination system was implemented theoretically and experimentally. A mathematical model was developed based on energy balance for each system component. Model validation was performed and a good conformity was seen between model and experiment results. The results showed that the maximum water production could be reached 11 Lit/m2 day and the water production cost was calculated about $0.0578 per liter [6]. Since the main part in HDH systems is the humidification unit, focusing on this would be useful in predicting the system performance. The performance of a cross-flow packed-bed humidifier was investigated experimentally by Sharqawy et al. [7]. In the humidifier presented by these researchers, hot water was sprayed over the packing where the air was flowing through it in a cross flow. The capacity, saturation efficiency, and specific energy consumption were calculated using the experimental data. The system performance was investigated in terms of the effects of operating conditions variations such as the mass ratio of water-to-air, the water inlet temperature, and the packing volume. The results showed that the specific energy consumption is almost constant with the changes in mass flow ratio, packing thickness, and inlet water temperature but the effectiveness increases by an increase in the number of humidifier units. The effectiveness and the number of the humidifier units were determined using the experimental data.

A solar multi-effect humidification dehumidification desalination system was investigated theoretically by Farid et al. in order to optimize the performance. In their study, the effects of some system components such as solar collector area, condenser, and dehumidifier on water productivity were investigated by mathematical modeling [8]. The modeling results showed that water productivity increases slightly by increasing the feed flow rate then decreases and the optimum feed flow rate was determined about 0.013 kg/s. Elsewhere, a 2-stage solar HDH system was investigated theoretically and a thermodynamic model was developed to design and optimize the system performance. In their

* Corresponding author.
E-mail address: y.ghalavand@eng.ui.ac.ir (Y. Ghalavand).

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work, the effect of the collector area, cooling water flow rate, feed flow rate, and system dimensions on water production rate was investigated on daily and monthly bases. It was found water production decreases by increasing in feed flow rate [9]. Another thermodynamic model was developed for a solar HDH system by Ben Bacha, who validated their model by comparing the simulation results and experimental data. The results showed that water production rate decreases by an increase in both feed and air flow rates [10].

Multi-effect or multiple injections systems are among the attractive fields in HDH desalination processes. A two-stage multi-effect desalination system using the humidification-dehumidification mechanism (and based on mass and energy balances) was developed by Kang et al. for each component of the system [11]. The model was solved by numerical methods and it was identified that water production rate in the lower stage decreases linearly by increasing the feed water temperature. Also, GOR increases at first and then becomes constant by increasing in air flow rate; however, GOR trend is increasing at first then decreasing by an increase in feed flow rate. In another work, a thermodynamic model was developed for multiple injections and extraction based on HDH process to investigate effects of enthalpy pinch and number of stages on system performance and water productivity. The results showed that GOR and water productivity increased by increasing the number of stages [12]. Energy recovery and the water recovery of closed air and water heated (CAWH) cycles were investigated for two conditions: zero extraction and single extraction processes. A model was developed for this system and the results illustrated that, at zero pinch point, GOR for zero extraction and single extraction are about 3.5 and 14, respectively. On the other hand, water recovery for zero extraction and single extraction were estimated to be 7% and 11%, respectively [13].

Several studies exist about the HDH process for system design and operating conditions optimization. In order to design and evaluate the system performance, a mathematical model was developed to estimate mass and heat transfer coefficients based on Reynold's and Prandtl's numbers by Al-Sahali and Ettouney [14]. In their study, system performance was presented as a function of system temperatures and air humidity. Their results showed that heat transfer coefficient varies linearly with cooling water temperature and air flow rate variations. A solar hybrid desalination process (HDH and water flashing) was investigated theoretically by Kabeel and El-Said [15]. System performance was assessed with respect to the variation of feed flow rate, air flow rate, cooling water flow rate, and cooling water temperature. The results showed a significant operational compatibility between the HDH method and water flashing desalination. In the reported hybrid system, maximum GOR and water productivity were reported to be equal to 4.5 and 11.14 kg/m2 day, respectively. The trend of solar air heater area variation showed a higher increase in the fresh water productivity compared to that of the solar water heater area variation. A close air and open water loop (CAOW) HDH system with solar evacuated tube heat exchanger were optimized by Zubair et al. [16]. The optimized system was investigated for the performance in different geographical locations, and the rate of water production and water production costs per liter were determined for each location. The water production costs for the locations were close to each other and water production cost was determined $0.032 to $0.038 per liter. Also, water/air mass flow ratio and GOR were calculated to be 1.8 and 2 respectively under the optimum conditions.

An HDH system was studied with exhaust gas energy driven theoretically by He et al. [17]. The results showed that the balance condition of the dehumidifier is inaccessible due to a negative specific entropy generation of the dehumidifier. High values of the component effectiveness and the initial temperature, as well as the vacuum environment, are beneficial to raise the performance of the desalination system and reduce the heat transfer surface area for the heat exchangers. The maximum obtained GOR was reported as 2.1.

The researchers in previous works usually focused on macroscopic modeling and thermodynamic modeling. In several works, the desalination system has been assumed as adiabatic. A new process was introduced as “humidification compression” (HC) in our previous published study [3]. Here, in this study, a modified mathematical model (with considering insulation heat loss effect) is developed to predict humidifier performance within the humidification compression process. The obtained profile of temperature, mass flow rate, humidity, and other parameters of the model are verified by experimental data and compared with the previous mathematical model [18].

2. Process description

In HC process, as described previously [3], feed water enters the heat exchanger and is heated by hot air discharged from the compressor. After heating, the water enters through the top of the humidifier and comes into contact with the air flowing from bottom to top of the column. The humidified air is discharged from the top and the concentrated water (brine) is discharged from the bottom of the humidifier. The discharged humid air enters a polytropic compressor and the air temperature increases during compression. Heated air enters the heat exchanger where it is cooled by the feed water. Then the cooled humid air enters the flash drum and the desalinated water is separated from the air. The saturated air is discharged from the top of the flash drum, returned to the humidifier after heating in the solar heater, and its pressure is decreased [18]. A process flow diagram of HC process is shown in Fig. 1. Also the experimental data used for model validation were obtained from the previously published work [19].

3. Model development

A mathematical model is developed to predict the humidifier behavior and operating conditions profile. In this study, the humidifier is a cylindrical column filled by packings to contact saline or brackish water and air with each other. The brackish water is entered into the column from the top and dried air is entered from the bottom of the column. A scheme of the humidifier is shown in Fig. 2. The humidifier used in this study has a 1500 mm packing section length and a 100 mm column diameter.

To develop the model for humidifier, the following assumptions should be made:

- The air and water flow pattern in the humidifier is plug.
- Radial changes of the parameters are ignored.
- All air and water physical properties are uniform along the column diameter.
- Mass and heat transfer area between brackish water and air are the same.
- No film is formed on the internal wall of the column.
- No heat loss is considered for the liquid phase.

Mass balance equation for water component in gas phase should be written to predict air humidity through the humidifier. To reach this aim, a control volume element should be considered according to Fig. 3.

In this element air stream is entered, evaporated water is absorbed with air, and the humid air is discharged from the element. Using governing equations for the element leads to Eq. 1.