Applied Thermal Engineering 90 (2015) 182–192

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Performance of a 3-stage regenerative desalination system based on humidification-dehumidification process

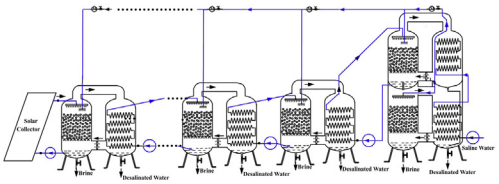
Huifang Kang*, Weining Luo, Hongfei Zheng, Zhiyi Yu, Peng Cheng

School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China

HIGHLIGHTS

- 3-stage regenerative desalination system is proposed.
- Desalination system is based on the humidification-dehumidification process.
- It realizes step utilization of heat, which decreases the temperature range.
- Mathematical model in each component of the system is developed.
- The gained output ratio (GOR) can reach 5.13.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 November 2014
Accepted 29 June 2015
Available online 10 July 2015

Keywords:
3-Stage
Regenerative
Desalination
Humidification-dehumidification

ABSTRACT

This paper presents a 3-stage regenerative desalination system based on humidification-dehumidification process. The sketch of 3-stage regenerative desalination process is given. It realizes the cascade utilization of thermo energy, which decreases the temperature range of the circulation. It improves the performance of the system enormously. A mathematical model based on mass and energy balances in each component of the system is developed. The numerical model is used to investigate the performance of this kind of installation exposed to a variation of the control parameters. The fresh water production can reach 91.1 kg/h and the gained output ratio can reach 5.13 when the temperature of saline water outlet from the solar collector reaches 85 °C.

1. Introduction

In many places, drinkable water is already a scarce goods and its lack will rise dramatically in the future. About 80 countries in the world are confronted with the problem of severe freshwater scarce [1]. The solar desalination systems based on the humidification-dehumidification (HD) principle are considered as the most viable among solar desalination systems [2]. Compared with other desalination systems [3–6], it is an innovative technology with promising diffusion and application due to its flexibility, simplified design, low maintenance, extended life time for over twenty years, low capital cost, construction and adaptation for use in rural areas to produce fresh water for drinking and irrigation [7–21].

The solar desalination systems based on the HD principle have undergone a substantial development over the recent decades owing to the pioneering work [7–21]. As the humidification-dehumidification desalination (HHD) system developed from the one-effect [7–9] to the multi-effect [10–14], the performance of the HHD system become well because of the recovery of the latent heat of condensation. However, most of those researches [7–14] focused on the one-stage HHD system. In one-stage system, the thermal energy recovery rate is low because of the difference of the

* Corresponding author. Tel.: +86 10 68914303; fax: +86 10 68949859.
E-mail address: kanghf@bit.edu.cn (H. Kang).

http://dx.doi.org/10.1016/j.applthermaleng.2015.06.102
1359-4311/

curves between the saturated wet air and the saline water [15,16]. Thus, Hou [16] proposed the concept of a two-stage HHD process based on the analysis of the pinch point temperature differences. For the same pinch point temperature difference of 1 °C, Hou demonstrated improved energy recovery with two stages.

McGovern et al. [17] further investigated the limits upon the energy recovery and the water recovery (product water per unit of feed) of closed air water heated cycles. This is done by considering heat and mass exchangers to be sufficiently large to provide zero pinch point temperature and concentration differences with in the humidifier and dehumidifier. The gained output ratio (GOR) increases and the recovery ratio (RR) decreases as the temperature range of the cycle is narrowed down, i.e. as the feed temperature increases or the top air temperature decreases. A single extraction is shown to be useful only when heat and mass exchangers are large in size. In addition, the effects of salinity and the validity of ideal gas assumptions upon the modeling of HD desalination systems are discussed.

Zamen et al. [18] evaluated multi-stage technique to improve the efficiency of the solar HD process through mathematical programming method. Result shows that multi-stage HD has good potential in process improvement. Also it is concluded that there are diminishing returns in energy recovery for an increasing number of stages when the pinch point temperature difference is fixed. Later they [19] experimentally evaluated a two-stage technique to improve the HD process in fresh water production from brackish water. According to the simulation results of the multi-stage process and the construction cost estimation, using a two-stage process is the most suitable choice that can improve important parameters such as specific energy consumption, productivity and daily production per solar collector area and thus, investment cost. A pilot plant was designed and constructed in an arid area with 80 m^2 solar collector area to evaluate the two-stage process. This unit was tested on cold and hot days. The effect of main parameters on fresh water production of the unit is studied. Experimental results show that two-stage HD desalination unit can increase heat recovery in dehumidifiers and hence, reduce thermal energy consumption and investment cost of the unit. Moreover, productivity can be increased by 20% compared with the single-stage unit.

About the same time, Zheng et al. [20,21] presented a two-stage multi-effect desalination system based on HD process. Compared with the previous multi-effect HD desalination systems, it recycled not only the latent heat of condensation but also the residual heat in the brine. A series of simulations and experiments were conducted to validate the developed models. The experimental results indicated that the yield of the unit can reach 63.6 kg/h.

According to the analysis of pinch point temperature differences [15–17], the decrease of the temperature range of the circulation will lead to the increase of the GOR. Based on the two-stage multi-effect desalination system designed by Zheng et al. [20,21], this paper will develop a novel multi-stage regenerative desalination system based on HD process, as shown in Fig. 1. The multi-stage regenerative desalination system realizes the cascade utilization of thermo energy, which decreases the temperature range of the circulation. It improves the performance of the system and the energy efficiency strongly.

2. Process description

Using air as carrier for vapor, the HHD system operates at atmospheric pressure. The process is based on moist air which is circulating in a closed loop. In the humidifier, the hot water is injected into the top of the humidifier. Hot water mist and saturated air mix with the rising air current toward the dehumidifier. Due to the increasing temperature of the air, the saturation humidity of the moist air in the humidifier increases. Then, the hot saturated air condenses in a large surface dehumidifier partially, producing fresh water that is gathered in the dehumidifier.

In this paper, a 3-stage system will be taken as an example to discuss this multi-stage regenerative desalination system, as shown in Fig. 2. The 3-stage desalination system consists of three closed loops for air circulation as shown in Fig. 2. The first stage is highest stage, the highest temperature circulation, the second stage is the middle stage, the middle temperature circulation, and the third stage is the lowest stage, the lowest temperature circulation. Six compartments constitute the installation: highest temperature humidifier (HTH), highest temperature dehumidifier (HTD), middle temperature humidifier (MTH), middle temperature dehumidifier (MTD), lowest temperature humidifier (LTH), and lowest temperature dehumidifier (LTD). The principle of the desalination process presented in this paper is as follows.

The circulation of the air in the closed loops may occur in forced convection. The forced convection is insured by a helical fan fixed at the bottom of air channel.

As show in Fig. 2, the saline water is heated by the solar collectors. Then, the hot water is injected into the HTH. Hot water mist and saturated air mixes with the rising air current toward the HTD. Due to the increasing temperature of the air, the saturation

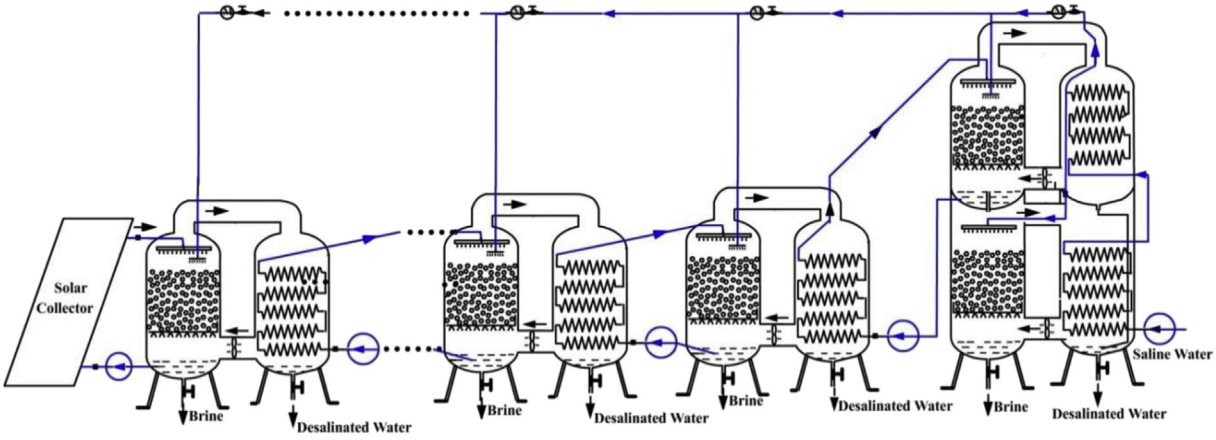


Fig. 1. Schematic drawing of the multi-stage regenerative desalination system based on humidification-dehumidification process.