Applied Thermal Engineering 100 (2016) 315–324

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Thermodynamic investigation of waste heat driven desalination unit based on humidification dehumidification (HDH) processes

W.F. He [a,*], L.N. Xu [b], D. Han [a], L. Gao [c], C. Yue [a], W.H. Pu [a]

[a] Nanjing University of Aeronautics and Astronautics, Jiangsu Province Key Laboratory of Aerospace Power Systems, Nanjing 210016, China
[b] FS-Elliott Co., LLC, Export, Pennsylvania 15632, USA
[c] Xi'an Thermal Power Research Institute Co., LTD, Xi'an 710000, China

HIGHLIGHTS

- HDH desalination system powered by waste heat is proposed.
- Performance of the desalination unit and the relevant heat recovery effect is calculated.
- Sensitive analysis of the performance for the HDH desalination system is investigated.
- Mathematical model based on the first and second laws of thermodynamics is established.

ARTICLE INFO

Article history:
Received 20 October 2015
Accepted 15 February 2016
Available online 23 February 2016

Keywords:
Humidification dehumidification desalination unit
Plate heat exchangers
Waste heat
Gained-output- ratio
Specific entropy generation

ABSTRACT

Humidification dehumidification (HDH) technology is an effective pattern to separate freshwater from seawater or brackish water. In this paper, a closed-air open-water (CAOW) desalination unit coupled with plate heat exchangers (PHEs) is applied to recover the waste heat from the gas exhaust. Sensitivity analysis for the HDH desalination unit as well as the PHEs from the key parameters including the top and initial temperature of the seawater, operation pressure, and the terminal temperature difference (TTD) of the PHEs are accomplished, and the corresponding performance of the whole HDH desalination system is calculated and presented. The simulation results show that the balance condition of the dehumidifier is allowed by the basic thermodynamic laws, followed by a peak value of gained-output-ratio (GOR) and a bottom value of total specific entropy generation. It is concluded that excellent results including the system performance, heat recovery effect and investment of the PHEs can be simultaneously obtained with a low top temperature, while the obtained desalination performance and the heat recovery effect from other measures are always conflicting. Different from other parameters of the desalination unit, the terminal temperature difference of the PHEs has little influences on the final value of GOR.

1. Introduction

Due to the severe water crisis all over the world, more and more attentions are focused on producing freshwater from the large amount of seawater. Hence, various desalination patterns, which can be mainly divided into the thermal method and membrane method, were proposed. The thermal method based desalination systems, such as multi-effect evaporator (MEE), multi-stage flash (MSF), thermal vapor compression (TVR), and mechanical vapor compression (MVC), were proposed and employed into various applications [1,2]. However, huge amount of energy consumption is required in such large scale desalination stations to obtain the freshwater production, while small scale applications with low efficiency are not considered. On the other hand, in the membrane method based desalination system [3], a continuous demand of electricity or mechanical energy should be first provided to drive the power machines.

As a result, for the occasions with small scale requirement of water production, such as the island and watercraft, the involved methods mentioned above will not be the suitable schemes. Nowadays, a promising desalination pattern using humidification dehumidification technology was proposed by Narayan et al. [4]. As one of the best schemes for small-scale water production applications, the HDH desalination systems have attracted extensive attention all over the world.

Narayan et al. [5] numerically simulated the performance of the water-heated, air-heated and the related modified air-heated CAOW patterns, and the design optimization of the HDH desalination system was also studied with a maximum water production rate for a given

* Corresponding author. Tel.: +86 02584892201; fax: +86 02584892201.
E-mail addresses: wfhe@nuaa.edu.cn; heweifeng_turbine@163.com (W.F. He).

http://dx.doi.org/10.1016/j.applthermaleng.2016.02.047
1359-4311/

heat input through the first-law based thermal analysis [6]. Furthermore, mass extraction and injection were taken into application to improve the performance of the HDH desalination system by both simulation and experiment approaches [7,8], and the significant effects were further found and validated. McGovern et al. [9] calculated the performance of water-heated CAOW desalination system with and without single extraction. It was found that for the cycles operating with an initial temperature of 298 K and a top air temperature of 343 K, the peak value of GOR reaches approximately 3.5 for a general system and about 14 for a single extraction system, while the value of recovery ratio is limited to approximately 7% without extractions and 11% with a single extraction. The calculation results showed that the method of single extraction is a good way to improve the performance of the HDH desalination system.

Solar energy was usually used as the heat source to drive the HDH desalination system, and it is especially suited for regions where the infrastructure and skilled manpower are deficient [10,11]. Hamed et al. [12] proposed a theoretical simulation model by applying energy equations taking each component into consideration to evaluate the relevant performance and the productivity of a solar desalination unit. Freshwater production of such a proposed system was calculated in two periods: the first one is from 9:00 am to 5:00 pm, while the second starts after preheating before entering the humidifier at 1:00 pm to 5:00 pm. The final results indicated that the highest freshwater production is found in the second period. Furthermore, a relevant experimental system was built to investigate the heat and mass transfer process within the system, and a great agreement of the comparison between experimental and theoretical results is presented, which gave the evidence that the proposed theoretical model is viable and can be applied for the solar HDH desalination system under different boundary conditions.

A parabolic trough solar collector (PTSC) was advised to be integrated into the open-air, open-water, air-heated HDH system by Al-Sulaiman et al. [13], and the corresponding thermodynamic performance was analyzed. The influences from the configurations of the solar air heater on the performance of the whole HDH desalination system were discussed. It was revealed that PTSCs are well suited for air-heated HDH systems for high radiation locations, and the HDH configuration with the air heater placed between the humidifier and the dehumidifier has a better performance and a higher productivity than other configurations.

Li et al. [14] used the evacuated tubes as the solar air heater to drive the HDH desalination system. It was found that the inlet water temperature in the humidifier was significant to improve the relative humidity of the outlet moist air as well as the outlet air temperature. The test results were valuable in the pursuit of the optimization for a solar HDH desalination system with the newly proposed solar air heater.

The patterns discussed in the above literatures are all analyzed based on the first law of thermodynamics; the corresponding research using the second law is also necessary to provide the optimization orientation [15,16]. Mistry et al. [17] accomplished the analysis of entropy generation for a CAOW desalination system with both air heater and water heater. The equations of both the entropy generation and exergetic were established. Based on the simulation results, it was proposed that entropy generation minimization analysis is necessary and helpful to identify the key components and operating conditions, which should be considered when designing the HDH desalination systems.

Obviously, the combination of solar energy and the HDH desalination is an excellent scheme to produce freshwater; however, the intermittence of the solar radiation is the inherent disadvantages for such solar-driven desalination systems. Thus, a more stable and economical heat source is needed to effectively drive the desalination system. Waste heat from the motor or thermal processes is an ideal option, especially applicable for China, which produces huge amount of waste heat due to the large population and rapid growth of industrialization. Cioccolanti et al. [18] investigated a single effect thermal desalination system, which is powered by the waste heat from a micro combined heat and power plants. Thermodynamic analysis and relevant simulation were completed to ascertain the layout of the thermal system, and then an experimental test was carried out to access the corresponding actual performance. It was found that the experimental results agreed very well with the initial predicted results. Elminshawy et al. [19] proposed a desalination unit coupled with both the solar energy and low grade waste heat as the driven power, and the viability by employing the exhaust gas from a combined gas turbine power plant for desalination system was also investigated. The related results exhibited great significance to optimize the conditions of waste gas to maximize the final fresh water production. He et al. [20] proposed a coupled system of the water-heated HDH desalination system and the plate heat exchangers, and the effect from the operation pressure on the performance of the desalination system was focused.

It can be concluded from the literature survey that the research on the humidification dehumidification technology is mainly focusing on the utilization of the solar energy, including the energy and exergy analysis. The waste heat was also applied to drive the desalination unit; however, the integrated systems between the humidification dehumidification desalination unit and the waste heat were seldom involved except the investigation from He et al. [20], which emphasized on the effects from the HDH system operation pressures. In this presented paper, the coupled desalination system with the plate heat exchangers and the HDH desalination unit powered by the waste heat are proposed. The corresponding mathematical model based on the first and second laws of thermodynamics is established and validated. Critical thermal parameters are appointed to implement the sensitivity analysis for the HDH desalination unit coupled with the PHEs, and the corresponding system performance and the heat recovery effects are calculated and illustrated. The research method as well as the corresponding obtained results provides the principles to define the configuration of the coupled HDH desalination system. Additionally, the entropy analysis offers the guidance of optimization to reduce the final investments.

2. Mathematical model of the HDH desalination system

The water-heated CAOW desalination system mainly contains a direct contact humidifier, a dehumidifier, and a plate heat exchanger, as shown in Fig. 1. It can be seen that there are two thermal cycles existing in the desalination system: the humid air cycle, which is responsible for absorbing and releasing water, and the seawater cycle. In the humidifier, heat and mass transfer simultaneously arises between the heated seawater and the low temperature humid air. In the dehumidifier, the air humidity ratio is reduced after the dehumidification process, and the fresh water is separated and produced.

Plate heat exchangers, consisting with the chevron shape plates, are used as the heat collector to recover the waste heat from the exhaust and heat the seawater from the dehumidifier for a top temperature. Evidently, the specific characteristics of the PHEs are significant for both of the performance of the desalination unit and the recovery effect of the waste heat.

2.1. Mathematical model of the PHEs

Counter flow is designed to enhance the total heat transfer coefficient of the plate heat exchangers. In the HDH desalination system, seawater should be heated to drive the whole system, and meanwhile the energy carried by the waste exhaust can be recovered. The temperature distribution along the flow direction in the heat exchanger is exhibited in Fig. 2, and the specific mathematical