Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Study on desalination of zero-emission system based on mechanical vapor compression ☆

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HIGHLIGHTS

- The zero-emission desalination systems are proposed.
- Performance of the single stage ZEDS is calculated.
- Double stage ZEDS is designed to improve the performance of the single stage system.
- Exergy analysis for the double stage ZEDS is achieved.

ARTICLE INFO

Article history:
Received 15 August 2015
Received in revised form 13 December 2015
Accepted 17 December 2015
Available online xxxx

Keywords:
Zero-emission desalination system
Mechanical vapor compression
Energy and exergy analysis
Compressor power
Stage number

ABSTRACT

Huge energy consumption is always essential in large-scale desalination technology, and relevant adverse impact on the surroundings from the concentrated solution with high salinity is ignored. In the paper, a zero-emission desalination system (ZEDS), including the single stage and the multi-stage, based on mechanical vapor compression (MVC) is proposed. Mathematical models of the desalination system corresponding to the proposed ZEDS are established, and then energy and exergy analysis are achieved to investigate the performance of the desalination system. It is found that the MVC based desalination system is available to achieve the aim of zero-emission. The simulation results both from the energy and exergy analysis show that the design of the multi-stage ZEDS is beneficial to reduce the total compressor power compared to the single stage system although the profit magnitude will decrease with the increase of the stage number.

1. Introduction

As an important method to relieve the shortage of freshwater resources all over the world, desalination technologies have attracted widespread attention in recent years. Generally speaking, the various desalination patterns can be divided into two types, the thermal method and membrane method [1,2]. The thermal method based desalination systems, such as multi-effect evaporator (MEE) [3], multi-stage flash (MSF) [4], thermal vapor compression (TVC) [5], and mechanical vapor compression (MVC) [6] were proposed and get into applications. Simultaneously, in the membrane method based desalination system [7], a continuous demand of electricity or mechanical energy should be first provided to drive the power machines.

Yılmaz [8] proposed a multi-effect evaporation desalination system with hybrid renewable energy as the power sources in Turkey, and the corresponding design and simulation method was established. The obtained results based on the mathematical models were compared with the literature, and the satisfactory comparison results indicated the superior potential of the renewable energy used in the multi-effect evaporation desalination system. As a result, some good rewards were obtained. Nuclear energy was used into the seawater desalination. Khamis [9] suggested some significant ideas to prevent the pathways of contamination for the desalination system. All possible contamination pathways were examined, and the preventive measures which were used both in design and operation of nuclear desalination plants were analyzed. Technoeconomic investigation of a novel MSF-MED desalination system was fulfilled by Mabrouk [10]. It was found that the superiority of the proposed integrated MSF-MED configuration for gulf council countries since the oil price is generally

☆ This paper was presented at the 7th International Conference on Applied Energy (ICAE2015), March 28-31, 2015, Abu Dhabi, UAE (Original paper title: "Study on zero-emission desalination system based on mechanical vapor recompression technology" and Paper No.: 126).

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http://dx.doi.org/10.1016/j.apenergy.2015.12.061
0306-2619/

Please cite this article in press as: Han D et al. Study on desalination of zero-emission system based on mechanical vapor compression. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2015.12.061

Nomenclature

Roman symbols

h	enthalpy (kJ kg^{-1})
Q	thermal energy consumption (MJ)
T	temperature (K)
ΔT	temperature difference (K)
W	compression power consumption (kW)
c_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
m	mass flow rate (kg h^{-1})
n	polytropic exponent
p	pressure (kPa)
P	compressor power (kW)
r	compression ratio
R	gas constant (kJ kg^{-1} K^{-1})
S	specific entropy (kJ kg^{-1} K^{-1})
w	specific work (kJ kg^{-1})
x	seawater concentration

Greek letters

α	activity
η	efficiency
λ	latent heat of vapor (kJ kg^{-1})

Subscripts

b	boiling
BPE	boiling point elevation
c	compressor
cs	concentrated solution
i	stage number; component number
inter	intermediate
m	mechanical
MVC	mechanical vapor compression
MVR	mechanical vapor recompression
s	saturation

subsidized. Lu [11] proposed an optimized mathematical model, which was modeled according to the LINGO algorithm and examined against the commercial desalination plants, and the corresponding applications of MEE-TVC based desalination system. The simulation results showed that the performance improvement as well as the decreasing energy consumption was accomplished through the optimization of integrating TVC suction position with operations of each effect. Han et al. [12] designed two mechanical vapor recompression (MVR) systems with the ammonium sulfate as the working fluid based on the self-heat recuperation technology, and the relevant energy saving performance was analyzed. It was found that the energy saving performance are more prominent compared to the conventional three-effect evaporation system. Khayet [13] tried to take use of solar energy into membrane desalination (MD) and reported on economics, energy analyses and costs evaluation of MD technology.

From the literature survey above, it was found that most of the existing desalination system will consume a large amount of energy both for the thermal or membrane desalination method, and the final concentrated solution from the desalination system is usually less than 6%. Furthermore, the final concentrated solution was always directly into the sea without any process. Hence, the adverse impact to the surrounding water resulting from the concentrated solution was ignored. Gina [14] proposed the concept of zero-emission desalination, which proposed the new requirements to energy conservation and environmental protection. The objective of zero emission can be achieved if the initial seawater into the desalination system can be concentrated with a final concentration exceeding 25% because under such mass concentration conditions, the crystal can be directly attained from the exhaust seawater when it is processed in the centrifugal separator or heated slightly under extra heat sources, and then the relevant influences to the surroundings will disappear. Due to the prominent energy conservation performance [15–17], single stage MVC thermal system has been widely used in many fields when the final mass concentration of the concentrated solution is less than 6%, while the high emission occasions were not applied, and the multi-stage MVC system was not involved. In this paper, the zero-emission desalination system based on mechanical vapor compression is proposed. The performance of the single stage ZEDS is first analyzed, and the novel multi-stage system is then designed to improve the performance of the desalination system through the energy and exergy analysis. The obtained results are significant to reduce the power consumption and the pollution toward the surroundings due to a mass concentration of the concentrated solution more than 25%, and provide useful references for the design and optimization of the desalination system.

2. Mathematical model of the ZEDS

2.1. Scheme of the ZEDS

Based on mechanical vapor compression, the single stage and multi-stage zero-emission desalination system are investigated, and the scheme of the single stage zero-emission desalination system is presented in Fig. 1. It is observed that the sensible heat from the condensate and concentrated solution is transferred to the initial seawater in the preheaters, 2–3 in HE1 and 2′–3′ in HE2, and then the preheated seawater evaporates, 5–6, the steam coming out under the effect of the released latent heat from the secondary steam. The evaporated steam leaves the separator from the top, 6–7, while the remaining concentrated seawater comes out from the bottom, 6–11. The separated steam is then induced to the compressor, and the corresponding temperature of the steam as well as the pressure is raised, 7–8, to build the temperature difference during the heat transfer process between the preheated seawater and the temperature raised steam, 8–9, which is just the aforementioned secondary steam. Finally, the condensate from the bottom of the evaporator and the concentrated seawater from the separator served as the heat source of the preheaters and then flow out of the MVC system.

For the inorganic salt seawater, the actual evaporation temperature is always higher than the saturated temperature for a certain pressure. Thus the relevant temperature difference is defined as the concept of boiling point elevation (BPE), and the value of BPE, calculated in Appendix A, will rise with the increase of the seawater mass fraction, shown in Fig. 2. As a result, to create the same heat transfer temperature difference, the concentration elevation of the seawater, which will contribute to a high value of BPE as well as a high pressure ratio of the compressor, is detrimental due to a higher power consumption of the compressor.

Furthermore, for the novel multi-stage ZEDS, shown in Fig. 3, which is constituted through the series connection of the single stage ZEDS, the initial seawater is preheated by the condensate from all the stages and the final concentrated solution. Furthermore, the discharged seawater will pose as the initial seawater of the next stage. Hence, for an objective of the same final mass concentration to the single stage MVC system, the mass flow rate as well as the pressure ratio of the steam in the compressors will be