Desalination 355 (2015) 197–203

Contents lists available at ScienceDirect

Desalination

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

Energy saving analysis for a solution evaporation system with high boiling point elevation based on self-heat recuperation theory

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HIGHLIGHTS

- The MVR system based on SHRT is proposed.
- The advantages of heat recovery for the multi-stage MVR system are presented.
- The solution boiling point elevation (BPE) is studied over the system investigation.
- Parametric and optimal analysis of the MVR system based on SHRT is achieved.

ARTICLE INFO

Article history:
Received 17 June 2014
Received in revised form 27 September 2014
Accepted 31 October 2014
Available online 6 November 2014

Keywords:
Self-heat recuperation theory (SHRT)
Mechanical vapor recompression (MVR)
Energy savings
Boiling point elevation (BPE)

ABSTRACT

This paper focuses on the application of self-heat recuperation theory (SHRT) in mechanical vapor recompression (MVR) evaporation systems when used to concentrate solutions with boiling point elevation (BPE). A nonlinear model is presented and used to analyze the advantages of heat recovery and multi-stage MVR over single-stage MVR. The model is then used to optimize the number of stages, evaporation temperatures, heat transfer temperature differences and stage concentration changes in relation to the compressor energy requirements. In comparison with single-stage MVR and conventional three-effect evaporation, multi-stage MVR with SHRT is shown to offer advantages when the number of stages is large, the evaporation temperatures are high and a large mass concentration difference between the outlet and inlet is required. However, the SHRT-based MVR system does not always yield energy savings when dealing with an inorganic salt solution with high BPE. A case study on concentrating a calcium chloride solution indicates that the SHRT-based MVR system uses more energy when the inlet mass fraction is over 38% compared to the conventional three-effect evaporation technology.

1. Introduction

Evaporation of inorganic salt solutions is widely utilized in the chemical and pharmaceutical industries. A large amount of heat is required to evaporate the water present in dilute solutions, making the overall process expensive and pollutive. However, these effects can be mitigated if the waste heat is recovered. Thus, energy savings are extensively emphasized all over the world, and many methods, which include multi-stage flash (MSF) [1], multi-effect evaporator (MEE) [2], thermal vapor compression (TVR) [3, 4], mechanical vapor compression/recompression (MVC/MVR) [5–11] and membrane [12], are proposed regularly.

Recently, to reduce the energy consumption of heat recovery, a self-heat recuperation technology (SHRT), incorporating compressors and heat exchangers based on exergy analysis was proposed to analyze the performance of several chemical processes [13]. In this technology, process units are divided into several functions to analyze the required heat, and all of the self-heat involved in the process stream is recirculated without adding additional heat. Therefore, the energy consumption during the process is reduced considerably.

Many energy saving schemes based on SHRT have been proposed. Kansha et al. [14] proposed a design methodology for heat integration distillation columns (HIDICs). A distillation process using an HIDIC was constructed, and the relevant energy savings were analyzed using a commercial process simulator to confirm further reduction of the energy consumption compared with other benchmark distillation processes. In addition, Kansha et al. [15] provided an innovative modularity of heat circulation for a distillation process, and their simulated results demonstrated that the energy consumption for a flash distillation process with SHRT is drastically decreased in comparison with a benchmark process that uses an external heat source. Matsuda et al. [16] used the actual operation data of the distillation process in a heavy

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http://dx.doi.org/10.1016/j.desal.2014.10.044
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chemical industrial field as an industrial application, and the initial feasibility study was undertaken by applying SHRT from an industrial point of view. In this way, an advanced industrial distillation process, in which all of the recuperated heat in the process was recirculated without any additional heat, can be developed. Furthermore, a case study from the viewpoint of cost savings was conducted with an example compressor. Matsuda et al. [17] proposed a self-heat recuperative distillation process, which shows prominent energy savings compared with a conventional distillation system. Long and Lee [18] examined an innovative SHRT-based process that circulates latent and sensible heat in the thermal process and applied it to the natural gas liquid recovery process. Kotani et al. [19] proposed a conceptual design of an active magnetic regenerative (AMR) heat circulator for self-heat recuperation to realize energy savings. It was found that an AMR heat circulator has significant potential to reduce the total energy consumption in a thermal process. Kansha et al. [20] applied SHRT to the distillation of crude oil, and their results showed that the crude oil distillation model based on SHRT produces significant energy savings. Kansha et al. [21] proposed a novel cryogenic air separation process, which reduced energy consumption by SHRT, and the relevant results showed that its energy consumption could be decreased by more than 36% compared with the conventional cryogenic air separation process when producing 99.99 mol% oxygen from air. Aziz et al. [22] proposed a novel drying system based on SHRT, which recuperates both sensible and latent heat, to reduce the energy consumption for biomass drying. Liu et al. [23] proposed an energy saving process for biomass drying to improve the overall energy efficiency by using SHRT for future industrial use. Aziz et al. [24] developed a brown coal drying process based on SHRT, which effectively recovers both latent and sensible heat to reduce energy consumption. Fushimi et al. [25] proposed an innovative drying process based on SHRT, which recovers not only latent heat but also sensible heat, with the purpose of saving drying energy. Aziz et al. [26] developed an advanced drying system for low rank coal drying with low energy consumption.

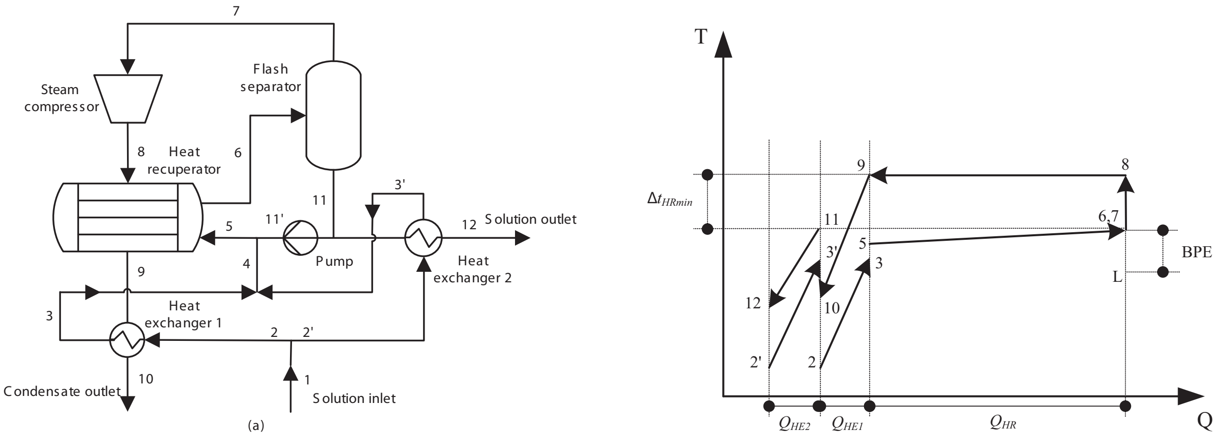
The literature shows that SHRT can achieve higher energy efficiency than that of the conventional processes. However, it raises the question of whether this technology can save energy in an MVR evaporation system with an inorganic salt solution with high BPE. In this study, SHRT is applied to integrate the heat utilization and compression process in an MVR evaporation system based on energy recuperation. According to this design methodology, a multi-stage MVR evaporation process of a highly concentrated inorganic salt solution is constructed, and the corresponding energy savings are calculated by using a commercial process simulator to confirm the reduction of energy consumption compared with other benchmark evaporation processes.

2. MVR evaporation system using self-heat recuperation theory

The schematic of the single-stage MVR evaporation system based on SHRT is shown in Fig. 1(a). It is shown that a flash separator is utilized to separate the mixture of the multi-component solution (6) at a temperature near the boiling point in the MVR evaporation system. The solvent of the solution will flash, flowing out from the top of the flash separator, because the saturated solution (6) flows into the flash separator, which supplies a large volume, and the concentrated solution (11) at the same temperature is also acquired from the bottom of the flash separator. Due to the boiling point elevation (BPE) of solution (11), which is defined as the temperature difference between the boiling temperature of the solution and the corresponding saturated temperature of the solvent (L), stream 7 is superheated but not saturated, and the relevant value of the BPE is determined according to the solution properties as well as the thermodynamic states.

The *T*–*Q* diagram of the MVR system is also shown in Fig. 1(b), in which $\Delta t_{HR\mathrm{min}}$ is the minimum temperature difference in the heat recuperator (HR). The sensible waste heat from the condensate (9) and the concentrated solution (some of stream 11) is absorbed by the inflow solution (1) in heat exchanger 1 and heat exchanger 2, respectively. While the latent heat from the pressure-raised stream 8 is released to saturate the solution in stream 5, taking the BPE into consideration in the heat recuperator, it is assumed that the temperature of the inflow and outflow, including the evaporated steam (7) and the concentrated solution (11), is the same. In addition, all of the self-heat is exchanged in the heat exchangers within the MVR system, which is consistent with the proposed SHRT. Moreover, as shown in Fig. 1(b), point L stands for the saturated temperature of pure steam 7, and the temperature difference between L and 7 presents the BPE of the solution.

The above MVR evaporation system is similar to those systems discussed in the previous literature [13]. For the MVR evaporation system with an inorganic solution at a high concentration, the $\Delta t_{HR\mathrm{min}}$ is necessary to keep an effective heat transfer process in the heat recovery system. The existence of BPE makes the steam evaporate to a superheated state in the flash separator, and the corresponding saturated pressure of steam (7) is lower than the pressure of solution 11. As a result, the energy conservation to recover the latent heat of steam (7) based on SHRT will result from the increased amplitude of the saturated temperature of the vapor in the compressor with the accumulation of BPE and the minimum temperature difference, $\Delta t_{HR\mathrm{min}}$, as depicted in Fig. 1(b). Additionally, the corresponding pressure increase should also be considered. Furthermore, the significance of BPE is especially important for the inorganic salt solution with a high mass fraction, and the corresponding pressure of the steam evaporated from the solution is



(a) Scheme of the thermal system (b) *T-Q* diagram

Fig. 1. Scheme of the single-stage MVR evaporation system based on SHRT. (a) Scheme of the thermal system. (b) *T*–*Q* diagram.