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Analysis of energy saving for ammonium sulfate solution processing with self-heat recuperation principle

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HIGHLIGHTS

- A concept of mechanical vapor recompression (MVR) evaporation system is proposed.
- Single and double-stage MVR system are designed and analyzed.
- The solution boiling point elevation (BPE) is studied over the system investigation.
- Parametric analysis of the MVR system is achieved.

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ABSTRACT

As an important production process, the evaporative concentration of the inorganic salt solution is extensively applied in the industry, and it is significant to investigate the energy saving potential of such evaporation systems. In the paper, taking the ammonium sulfate solution for example, the self-heat recuperation technology (SHRT) is utilized to design two mechanical vapor recompression (MVR) systems, and the relevant energy saving performance is analyzed. It is found that the designed systems, which are satisfied with SHTR, enable the recovery of the sensible and latent heat of the emission solution without any additional heat, and compared to the conventional three-effect evaporation system, the energy saving performance are more prominent. However, in view of the existence of the boiling point elevation (BPE) for the inorganic salt solution, a maximum reduction amplitude of 40% of the energy saving performance for the double-stage MVR system is obtained compared with the single-stage MVR system. As a result, it is concluded that the only satisfaction to the SHRT is not enough, and the pattern of the MVR system should also be considered to ensure a prominent energy saving performance.

1. Introduction

Evaporation concentration and crystallization of the ammonium sulfate solution has been widely used in the modern chemical plants. A large amount of latent heat is required when phase change happens for the solution, and thus the energy consumption during the evaporation crystallization process is very high. In order to improve the overall technical and economic competitiveness of the evaporation concentration and crystallization technologies, many kinds of energy saving methods with different heat recovery levels have been developed and applied to reduce energy consumption per unit product, such as multi-stage flash (MSF) [1,2], multi-effect evaporation (MEE) [3,4], thermal vapor compression (TVR) [5] and mechanical vapor recompression (MVR) [6–8]. Applications of these heat recovery technologies have made great contribution to the industrial energy saving. Among these technologies, the MVR is one of the effective energy saving technologies, in which the effluent vapor is totally compressed to increase its sensible enthalpy to heat the feed [6], and it shows advantages with the low energy consumption and simple system structure compared with that of MSF, MEE and thermal vapor compression. However, many of the published studies pertained to single-stage MVR, and the increasingly serious energy crisis requires urgent researches on further energy saving for the MVR system [8]. Lin L. [9] proposed a double-stage mechanical vapor recompression evaporation system for the treatment of highly concentrated inorganic salt wastewater, and its characteristics were analyzed taking ammonium sulfate

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Nomenclature

Roman symbols

H	enthalpy, kW
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/K
m	mass flow rate, kg/h
n	polytropic exponent
p	pressure, kPa
q	low heat value of standard coal, MJ/kg
r	compression ratio
R	gas constant, kW/kg/K
w	specific work, kW/kg

Greek letters

η	efficiency
λ	latent heat of vapor, kJ/kg

Subscripts

b	boiling, boiler
BPE	boiling point elevation
c	compressor
e	electricity
LHV	low heat value
m	mechanical
MVR	mechanical vapor recompression
s	saturation
TE	three-effect

wastewater as the treated solution. It was found that the system can be used to treat highly concentrated inorganic salt wastewater and can save energy.

Simultaneously, an energy saving theory of self-heat recuperation technology (SHRT) has been developed recently, which enables the recovery both of the sensible and latent heat without any additional heat in an evaporation process [10]. As a result, the heat of the process stream was circulated perfectly without additional heat, and the energy consumption can be reduced considerably. Therefore, a great energy-saving potential was achieved through the application of SHRT in the field of distillation [11–16], drying [17–21] and gas separation processes [22].

However, despite the extensive research focus on the SHRT in the field of distillation, drying and gas separation processes, the theory has never been applied to the evaporation crystallization system of inorganic salt solution with boiling point elevation, which is especially significant for the performance of the corresponding system. In the paper, the self-heat recovery technology is used to design two mechanical vapor recompression (MVR) systems, in which the sensible and the latent heat are recovered, and the relevant energy saving performance is analyzed comparing with the conventional three-effect evaporation system. The corresponding reasons for the energy saving potential in the evaporation system of ammonium sulfate solution are discussed, and the parameters such as the boiling point temperature, minimum temperature difference in the heat exchanger and emission mass concentration of the solution outlet of first stage are discussed. The paper provides the references to design and optimize the MVR system for a prominent performance of energy saving.

2. Energy saving evaporation system of ammonium sulfate solution based on self-heat recuperation technology

According to the principles of the self-heat recuperation technology, the MVR self-heat recovery systems with single-stage and double-stage are designed, respectively. Facilitating to compare energy saving performance of the above two systems, the same feed capacity, total evaporation capacity, initial feed concentration, emission concentration and feed temperature and evaporative temperature are assumed.

The single-stage MVR system is presented in Fig. 1. As shown in Fig. 1(a), the feed with an initial concentration through the PHX1 and PHX2 absorbs the sensible heat from the condensate water and emission solution, and then evaporates through absorbing the latent heat of the secondary steam in HX1. Finally, the feed flows out of the evaporation system with the final required emission concentration. It is found that the recovery of the latent heat from the secondary steam is implemented through the pressure rise in the compressor for the scheme demonstrated in Fig. 1, and the feed is preheated by the effluent solution and the condensate water.

It is also seen from Fig. 1(b), when the SHRT is directly applied to deal with the high concentrated inorganic salt solution with obvious boiling point elevation such as ammonium sulfate solution, the secondary vapor is superheated [7] with the corresponding saturated vapor temperature, T_s, and its boiling point elevation was the temperature difference between T_b and T_s. In order to supply the necessary minimum heat transfer temperature difference in HX1, a big compression ratio, r, is required for the compressor. It can be inferred that a large amount of compressor power will be consumed for the compression ratio, r, to elevate the saturated temperature of the secondary vapor compared with the no BPE condition. Therefore, if an effective method is adopted to reduce the average equivalent boiling point elevation during the whole evaporation process, the compression ratio will be decreased as well as the overall compression power consumption of the single-stage MVR evaporation system.

Based on the above analysis, a double-stage MVR system is also designed as shown in Fig. 2. The initial feed flows through the PHX1 and PHX2 absorbing the sensible heat from the condensate water and the emission solution, and then enters HX1 to evaporate through absorbing the latent heat from the condensate secondary steam in the first stage. After the partial concentration in the first stage, the solution at state 5 flows into HX2 located in the second stage to evaporate. Finally, the condensed solution is exhausted from the MVR system at the requirement emission concentration. It can be seen from Fig. 2(b), different from the single-stage scheme, part of the water is evaporated from the initial solution at the first stage, and the boiling point elevation at the first stage, which is the temperature difference between T_b and T_{s1}, is lower than that of the second stage. The boiling point elevation at the second stage is the same as the single-stage MVR system. The compression ratio at the first stage can be reduced due to a low boiling point elevation at the low emission mass fraction. Therefore, it is inferred that the overall compression power consumption of the double-stage MVR system based on SHRT will be reduced.

The vapor compressor in the MVR system is used to raise the pressure of the secondary steam, and the corresponding saturated vapor temperature is obtained to provide a minimum temperature difference during the preheating process for the feed solution. No additional energy is needed in the MVR system because all the