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Advanced energy saving in the evaporation system of ammonium sulfate solution with self-heat recuperation technology

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Abstract

A concept of a novel double-stage mechanical vapor recompression (MVR) evaporation system based on the principles of self-heat recuperation technology for ammonium sulfate solution processing is proposed. In the paper, the single-stage and double-stage MVR evaporation systems for ammonium sulfate solution are designed and analyzed. A parametric study is performed to investigate the effects from the emission concentration of the first stage, the evaporation temperature and the temperature difference (TD) between the condensing steam and the boiling solution on the power consumption and heat transfer. During the investigation, the initial ammonium sulfate solution with a concentration of 3% is concentrated to the saturation solution, which has a concentration of 53%. The results show that despite the satisfaction to the principle of self-heat recuperation technology for the two systems, the boiling point elevation will result in a high energy consumption for the compressor in the single-stage MVR system, while the double-stage MVR evaporation system has an obvious energy saving effect with an improved amplitude of 40%.

Keywords: self-heat recuperation technology, mechanical vapor recompression, energy saving, evaporation, boiling-point elevation.

1. Introduction

Researchers and engineers have developed heat recovery methods for evaporation crystallization process, such as multi-stage flash (MSF), multi-effect evaporator (MEE), thermal vapor compression (TVR) [1, 2], and mechanical vapor recompression (MVR) [3,4] to reduce the energy consumption, of which the efficiency is higher than that of MSF, MEE and thermal vapor compression [3].

Recent developments in self-heat recuperation technology (SHRT) have enabled the recovery of both the sensible and latent heats without any additional heat in a process. To recirculate the self heat in the process, the cooling load is recovered by compressors and exchanged with the heating load. As a result, the heat of the process stream is circulated perfectly without additional heat, and the energy

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consumption for the process can be reduced considerably [5]. SHRT shows a great energy saving potential in distillation, drying, and gas separation processes [6]. However, SHRT has not been applied to the evaporation crystallization system.

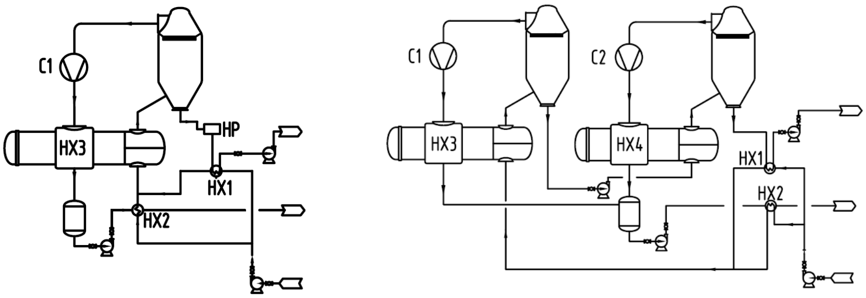
This work aims to evaluate the energy saving potential by applying SHRT to evaporation systems of ammonium sulfate solution. Two different evaporation systems are designed, and the relevant energy saving effect is analyzed and compared. Reasons for energy saving in the evaporation systems of ammonium sulfate solution are discussed and factors such as the boiling temperature, minimum temperature difference in the heat exchanger, mass concentration of the solution at the outlet of the first stage are evaluated.

Nomenclature

BPE	Boiling Point Elevation, °C	*Q*	heat load, kW
w	specific work, kW/kg	*P*	pressure, Pa
T	temperature, K	m	flow rate, kg/s
X	mass concentration, %	TD	temperature difference, °C
Subscripts			
b	boiling temperature	*f*	effluent stream
h	high	i	inlet
o	outlet	*l*	low
comp	compressor		

2. Energy saving evaporation system of ammonium sulfate solution

Self-heat recuperation technology facilitates the recirculation of both latent and sensible heat in a process, and reduces the energy requirements using compressors and self heat exchangers based on energy recuperation [5]. The designed single-stage and double-stage MVR system are presented in Fig. 1, respectively. The feed with initial concentration through the HX1 and HX2 absorbs the sensible heat from the condensate water and emission, and then evaporates under the latent heat of the secondary steam in HX3. For the double-stage system, the obtained concentration of the first stage flows into HX4 in the second stage to evaporate, and then the solution is exhausted.



(a) (b)

Fig. 1 Single-stage and Double-stage MVR process with self-heat recuperation technology

3. Process modeling of evaporation system of ammonium sulfate solution

The industrial production is always a steady-state process. As a result, the current investigation focuses on the analysis and comparison of the energy saving performance for the two systems based on the mass and energy balance. The feed into the system is preheated in the heat exchanger, and ninety seven percents of the released heat from the hot material is absorbed by the cold side in the heat exchanger. The relevant heat is expressed as:

$$Q = mC_p(T_h - T_l) \tag{1}$$

The heated material by the waste heat, which is not boiled, is again heated in the high temperature heat pump with a COP of 2.0 to the boiling point.

For the compressor, the specific power consumption is given as:

$$w = \frac{nRT_i}{\eta_{comp}(n-1)}\left[\left(\frac{p_o}{p_i}\right)^{(n-1)/n} - 1\right] \tag{2}$$

where η_{comp} is calculated by multiplying the thermal compression efficiency, η_{comp}=60%, p_o and p_i the outlet and inlet pressure of the compressor, respectively.

The saturated temperature of the steam before the compressor:

$$T_i = t_b - BPE + 273 \tag{3}$$

The value of the BPE is expressed as:

Table 1. BPE of ammonium sulfate solution at 1atm

Mass concentration of solution, %	BPE, °C	Mass concentration of solution, %	BPE, °C
3	0.22	30.56	3
6	0.45	36.71	4
9	0.67	41.79	5
12	0.9	45.37	7
13.3	1	49.77	10
23.41	2	53.55	15

For the double-stage MVR system, the emission concentration from the first stage is variable. As a result, the total power is a function of the emission concentration from the first stage, and the minimum total power can be obtained by the extreme value method.

4. Results and discussion

The index of standard coal, which has a value of 7000kcal/kg, is applied to assess the energy saving performance in the paper, and the energy saving effect of the single and double-stage is compared with the three effect evaporation system by converting the consumed electricity of the compressor in the MVR system and the heat steam of the evaporation system to the standard coal. The thermal efficiency of the boiler in the power plant is fixed at 85%, and the power generation efficiency is 36.6%. The energy efficiency ratio of the three effect evaporation system is 0.42, which implies 0.42kg of heat steam is needed to evaporate 1kg of water.

All of the parameters for calculation are listed in Table 1.

Table 2. Parameters for calculation

Item	value
Evaporation capacity, kg/h	1000
Mass concentration of feed flow, %	3
Temperature of feed flow, °C	25
Range for mass concentration of final effluent flow, %	53
Difference between the hot flow outlet and the cold flow inlet, °C	10
Range for the temperature difference in heater, °C	4、6、8、10、12、14、16

4.1. Analysis of the compressor power consumption for the single-stage MVR system at constant evaporation capacity

Figure 2 shows the relation between the compressor power for one tonne of evaporation capacity and the temperature difference in the heat exchanger. It is evident the consumed power rises with the increase of the temperature difference and the emission concentration, and the obvious increase heterogeneity appears when the emission concentration rises. Little difference of the consumed power is obtained until the emission concentration of 23%, and then the increase amplitude rises significantly. The increase amplitude of the compressor power is about 85~300% at the evaporation temperature, 60℃, emission concentration, 53%, compared to the conditions at low concentration, which is attributed to the BPE.

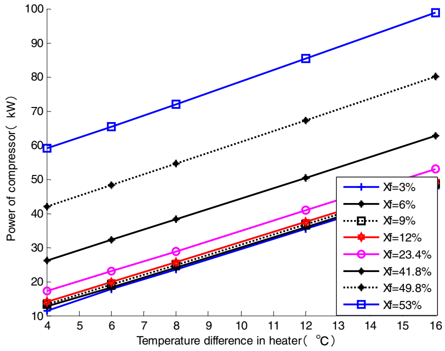
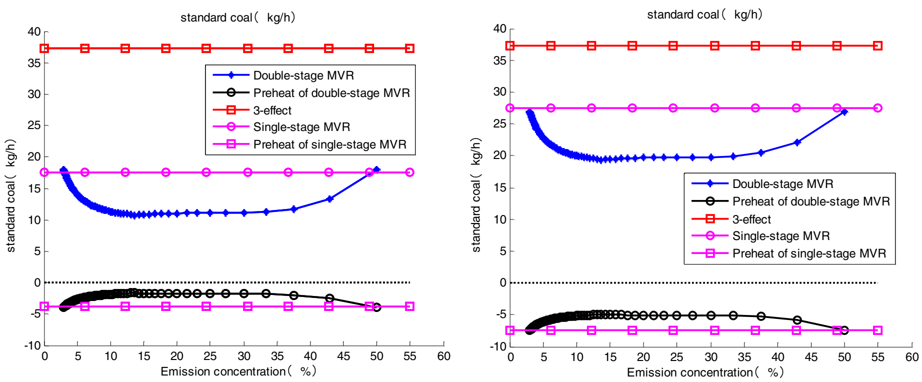


Fig. 2 Power of compressor for 1000kg/h vapor with temperature difference in heater

4.2. Power performance of the compressor in the MVR system



(a) TD=8°C (b) TD=16°C

Fig. 3 Standard coal needed at different temperature difference in the heater for three systems

The consumed standard coal for the single, double-stage MVR and the three effect evaporation system at the heat transfer temperature difference of 8℃ and 16℃ are presented in Fig. 3. It is seen that the three effect evaporation system has the highest coal consumption at the concentration range of 3% to 50% for the emission, while the double-stage MVR system has the lowest. For the heat transfer temperature difference of 8℃， the coal consumption of the single-stage MVR system is only 52% of the three effect system, and the double-stage MVR system has a saving amplitude of 40% compared to the single-stage MVR system. When the heat transfer temperature difference is 16℃， the coal consumption of the single-stage MVR system is only 70% of the three effect system, and the double-stage MVR system has a saving amplitude of 23% compared to the single-stage MVR system.

The standard coal corresponding to the compressor power of the single-stage MVR system and the minimum coal consumption of the double-stage MVR system at different heat transfer temperature difference are shown in Fig. 4, and the emission concentration differs from 3% to 50%. It is clear that the consumed coal for the two systems both rises linearly with the increase of the heat transfer temperature difference. Compared to the single-stage MVR system, the energy saving amplitude of the double-stage MVR system is 55% at the heat transfer temperature difference of 4℃， while it is 30% at 16℃. The waste heat in the two systems is able to preheat the feed to the boiling point, 60℃, and the surplus heat rises with the increase of the heat transfer temperature difference. The waste heat of the double-stage MVR system is smaller than that of the single-stage one due to the more significant energy saving effect.

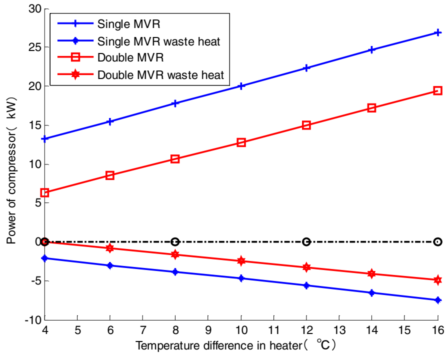


Fig.4 Standard coal needed by single, double-stage MVR system with the temperature difference in the heater

5. Conclusions

It is found that the energy saving effect of the single and double-stage MVR system, both of which are satisfied with the self-heat recuperation technology with no additional heat, are different in the paper. The energy saving superiority of the double-stage MVR system rises with the increase of the evaporation concentration of the ammonium sulfate solution, and an energy saving amplitude from 30% to 55% will be achieved at the saturated concentration.

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