

## Energy-Saving Study of a System for Ammonium Sulfate Recovery from Wastewater with Mechanical Vapor Compression (MVC)

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**Abstract:** In this study, a new two stage Mechanical Vapor Compression (MVC) system which is used to recycle ammonium sulfate is investigated. In evaporation process, there are many efficient ways such as multiple-effect evaporation, multi-stage flash, thermal vapor compression, and mechanical vapor compression and so on. In these ways MVC is considered to be more effective. Now, almost all of the MVC systems in the literatures are about one stage structure. However, in the other process such as continuous crystallizer, if one stage MVC system is adopted, a lot of energy will be wasted. Therefore, in order to further save energy, a new system should be proposed. In this study, a new two stage MVC system is proposed and analyzed using the software of ASPEN PLUS. The first stage is a forcible recycle evaporator with MVC and the second one is a forcible recycle crystallizer with MVC. The energy consumption is discussed as a function of the middle concentration and the operating temperature. The results show that the compressor power decreases with the increase in the operating temperature and the optimal compressor power is obtained when the mass concentration is about 32%. Compared with one stage MVC system the running cost of the new system can be saved 29.2% and more than 25.8% of the energy can be saved. Additionally, it can save running cost over 42.2% and save energy more than 59.6% compared with the conventional multi-effect system.

**Key words:** Ammonium sulfate wastewater, ASPEN PLUS, energy saving, mechanical vapor compression

### INTRODUCTION

Evaporation is the most widely-used process in chemical, food, pharmacology and water treatment industries. It consumed huge amount of energy. Therefore it is significant to improve energy utilization in evaporation process. Many ways have already been proposed to increase the efficiency of the evaporation processes such as multiple-effect evaporation, multi-stage flash, thermal vapor compression, and mechanical vapor compression and so on. In these processes, Mechanical Vapor Compression (MVC) is considered to be more cost-effective (Darwish and El-Dessouky, 1996; Aly and El-Fiji, 2003). In the MVC system the compressor pressurizes the incoming steam from the evaporator and this compressed steam releases its heat for the evaporating solution. So the latent heat of the steam which is condensed by condenser in traditional processes is recovered. The system is compact, confined and does not require external heating source, and it is just driven by electric power in the absence of the down stream condenser and cooling water requirements (Al-Juwayhel *et al.*, 1997). The system also has the following advantages, such as:

- Low corrosion rate
- Operation reliability and flexibility
- High thermodynamic efficiency
- Minimal scaling rates
- Low energy costs (Mabrouk *et al.*, 2007)

Many literature studies about MVC system were reported in the field of desalination. Most of them are about single effect systems. (Veza, 1995) reported the two low-temperature mechanical compression systems. Each of them has a production capacity of 500 m<sup>3</sup> per day. It is pointed out that the energy consumption is about 10.4-11.2 kWh/m<sup>3</sup> when the operating temperature is about 60°C. (El-Sayed, 1999) studied the performance and the cost of three large mechanical vapor compression systems. It was concluded that the cost could be reduced as much as 30% and the efficiency increased by about 50%. Furthermore, some mathematical models of the MVC system have been presented. (Ettouney *et al.*, 1999) developed a model of the mechanical vapor compression system and analyzed the specific power consumption as well as the specific heat transfer areas. He found that the specific power consumption decreases at the minimum temperature difference between the boiling brine and the

steam condensate as the specific area increases. (Aybar, 2002) constructed a simple model and analyzed the effects of the main parameters on the system performance. The results show that the consumption of specific energy was 11.47 kWh/ton. (Ettouney, 2006) presented a comprehensive mathematical model of the mechanical vapor compression system and analyzed the effects of the product flow rate, brine boiling temperature as well as dimensions of evaporator tube on the system performance. (Mussati *et al.*, 2009) proposed a simple optimization mathematical model of the system and the results got by the model were consistent with the reported values by other literatures.

Additionally, (Mabrouk *et al.*, 2007) investigated the multi-stage flash with the mechanical vapor compression system. It was observed that the performance ratio of the proposed system was 2.4 times the performance ratio of conventional multi-stage flash system. The heat transfer and exergetic efficiency of the proposed system was 57% and 67% higher than that of the conventional multi-stage flash system, respectively. (Nafey *et al.*, 2008) compared effects of using and un-using external steam to initiate the process and the results showed that the performance ratio of the proposed system with external steam is 8% less than that without external steam. MVC system can be integrated with other friendly renewable systems such as: solar system (Helal *et al.*, 2007), photovoltaic system (Nafey *et al.*, 2006), and wind system (Karameldin *et al.*, 2002; Forstmeier and Mannerheim, 2007).

In experimental aspect, the application of the MVC system was rarely reported in recent years. (Aly and El-Fiji, 2003) reported a single effect case located in the heat transfer laboratory of the Atomic Energy Authority of Egypt with a capacity of 5m<sup>3</sup>/day. Results indicated that with the increasing in the operating temperature the production rate increases and a high evaporator temperature is good for the heat transfer coefficient. (Bahar *et al.*, 2004) experimentally investigated a two-effect mechanical vapor compression system with a capacity about 1 m<sup>3</sup>/day. The results indicated that the brine recirculation rate had no effect on the performance ratio. Meanwhile, a lower concentration and a higher compressor speed led to a better performance. The highest average performance ratio is 2.52.

In other fields, the application of the MVC system was also mentioned more or less. (Grattieri *et al.*, 2001) reported the application of mechanical vapor compression in the food industry and it is experimentally proved that this kind of system was energy-saving and economical. (Mounir *et al.*, 2005) presented a system treating pollutant concentration with mechanical vapor compression and analyzed the effects of the temperature difference in evaporator-condenser on the cost of the system. The results showed that the optimum cost was obtained when the temperature difference is between 2 and 3.

All of above are about one stage MVC system. However, in the continuous crystallizer process, if one stage MVC system is used, a lot of energy will be wasted.

This is because the crystal generate only when the solution reach saturation, where the solution has a high boiling point rise. Hence, if some of water evaporated before the solution reach saturation, the boiling point rise of the solution is low and then energy consumption is reduced. In this study a new two stage mechanical vapor compression system which is used to recycle the ammonium sulfate is presented. The system is a composition of two MVC stages. The first stage is used to evaporate the wastewater and the second one is the evaporative crystallization. The effects of the middle concentration and operating temperature on the energy consumption of the system were investigated using ASPEN PLUS software. Then an experiment was carried out to check the simulation results. In the end, some economic analysis and energy-saving diagnosis of such MVC system are provided.

#### Process description and model:

**System description:** A schematic diagram of the system is shown in Fig. 1. The system mainly consists of two MVC stages. They are forced circulation evaporator and forced circulation crystallizer respectively. The waste solution is introduced into the first stage and evaporated to an intermediate concentration firstly. Then the evaporated solution is discharged into the second stage in which the solution is evaporated further and the ammonium sulfate is crystallized. The detailed process describe as follows.

The intake waste solution which is a mixture of water and ammonium sulfate introduced into the pre-heater and exchanges heat with the condensate water coming from the condensate tank. Then, the preheated feed leaving the pre-heater is mixed together with the recycled concentrated solution and pumped to the tube side of the heat exchanger 1 by the recycle pump 1. In the heat exchanger 1, the mixed solution absorbs the heat of condensing steam and its temperature increases to its designed value. After that, the heated solution enters the flash vessel 1, where an amount of water vapor is formed by the flashing process. The flashed-off vapor is induced into the compressor through a wire-mesh mist eliminator on the top of the flash vessel 1, which is used to separate water droplets. Passing through the compressor, the vapor is compressed and its temperature and pressure are raised. Then the compressed vapor is forced inside the shell of the heat exchanger 1, where it releases its sensible heat and latent heat to the solution of the tube-side. Condensed water is discharged into the condensate tank and it preheats the intake waste solution to hot stream. The concentrated solution exiting the flash vessel is split up into two portions. One is recycled solution and goes on to recycle. The other flows into the second-stage system through pump 1.

The feed coming from the first-stage is mixed with the recycled slurry which contains ammonium sulfate crystals. This slurry is introduced into the heat exchanger

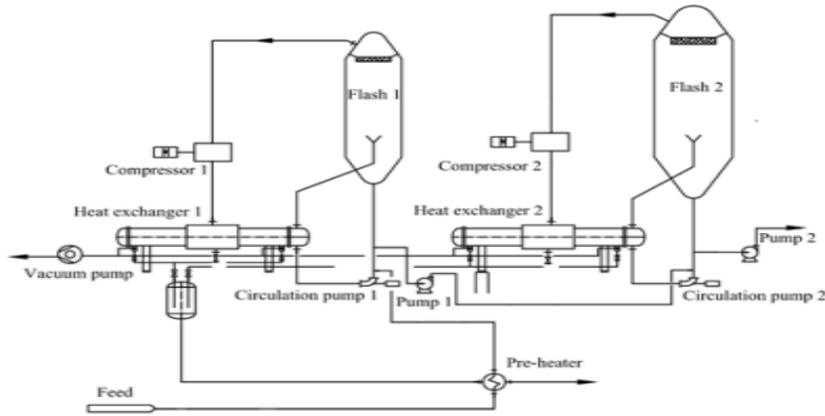


Fig. 1: Schematic diagram of the system

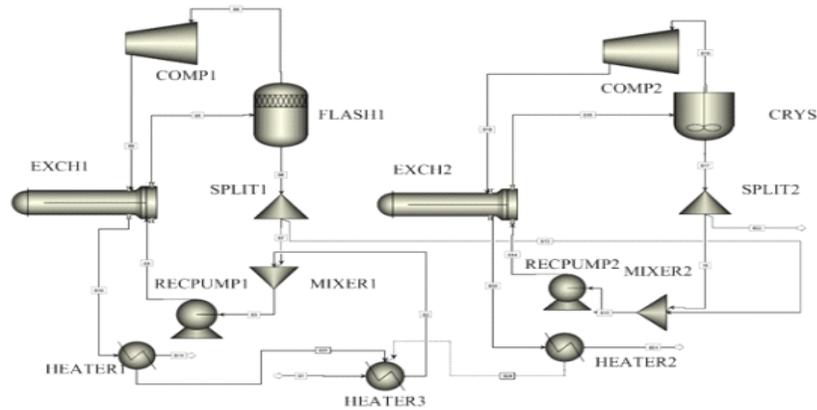


Fig. 2: Model of the system in ASPEN PLUS

2 and is heated to its designed temperature. After that, the slurry flows into the flash vessel 2 in which the vapor is flashed and sends into the compressor 2. Upon compression, the vapor is forced in the heat exchanger 2 and condensed into water and discharged condensate tank. In the flash tank 2, ammonium sulfate crystals generate gradually since the concentration of solution is increased and exceeds the solubility of the ammonium sulfate. This slurry exits the flash tank 2 and split to two parts: the first part goes on to the recycle in the second-stage and the second part is discharged to the next process.

Vacuum pump is charged with the system to produce the system vacuum and extract the non-condensable gases from the system so that a good heat transfer process can be attained during the operation of the system.

**Model of the system:** In this study ASPEN PLUS is chosen as the simulation tool to model the system and analyze the energy consumption. As process simulation software, ASPEN PLUS can simulate the steady state

process in the chemical industry. It is widely used to investigate the energy questions. Also ASPEN can provide a favorable calculation method that ensures convergence of material and energy in the loop process. In ASPEN PLUS there are many built-in model blocks such as heaters, separators, mixers, splitters, compressors and so on. So it is easy to create the model of researched system. Additionally, ASPEN PLUS has many databases including physical, chemical and thermodynamic properties for a wide variety of chemical compounds, as well as selectable thermodynamic models required for accurate simulation of any given chemical system.

The ASPEN PLUS flow sheet for the MVC is shown in Fig. 2. The pre-heater is heaters as shown in the flow sheet. HEATER1 and HEATER2 simulate the hot side and HEATER3 simulate the cold one. The condensed water from EXCH1 and EXCH2 flows into HEATER1 and HEATER2 respectively, in which they are cooled and releases heat into HEATER3. The flow coming from the cold side absorbs and so makes the temperature rise. The

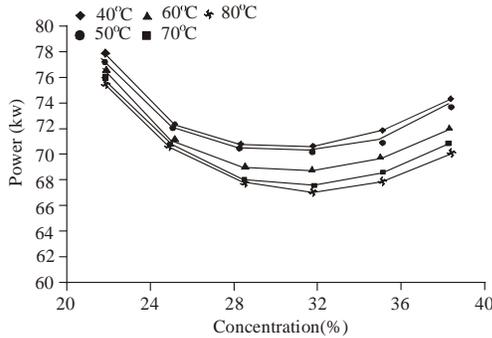


Fig. 3: Effect of the middle concentration and the operating temperature on the total compressor power.



Fig. 4: The view of the system located in Jiangsu, China

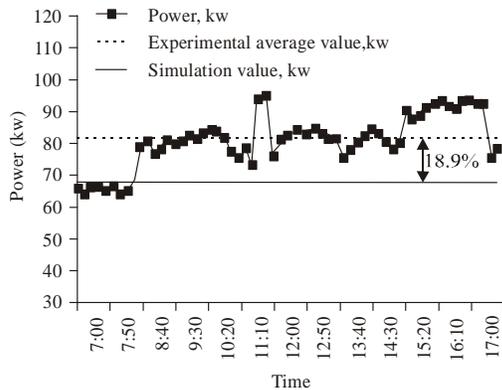


Fig. 5: Experiment results of the compressor

crystallization process of the second stage is simulated by the crystallizer module. Considering that the simulation is the steady state process and the operating status can be set before computations, the vacuum system is not simulated.

### SIMULATION RESULTS AND DISCUSSION

When the system is simulated there are some assumptions. Firstly, the heat exchanger, the flash vessel, the compressor, the pump and the pre-heater are considered as adiabatic stages and the heat losses are negligible. Secondly, there is no non-condensable gas.

Table 1: Parameters of the experiment

Parameters	Value
Intake flow rate (kg/h)	2500
Intake flow temperature (°C)	30
Intake flow pressure (atm)	1 atm
Ammonium sulfate concentration (%)	20
Compression ratio of compressor 1	1.52
Compression ratio of compressor 2	1.68
Operating temperature of two stage (°C)	70

The parameters for the simulation are shown in the Table 1. The middle concentration and the operation temperature influence the system energy consumption. The results generated using ASPEN are shown in Fig. 3. In Fig. 3, every curve shows the variation of compressor power (containing compressor1 and compressor2) with increasing concentration for different operating temperatures. It can be known that there is a minimal value for every curve when the middle mass concentration is about 32%. The reason is that the influence of middle concentration on the two stages is different. With the increasing in the middle concentration, the vapor coming from flash1 increases and hence, the vapor is flowing into compressor1 increases. This makes compressor power increase. However, vapor that generated by the flash2 decreases and thus, the power of compressor 2 decreases with increasing concentration. As a result, there is an optimal point for each operating temperature.

Additionally, it can be seen in the Fig. 3 that compressor power decreases with increasing operating temperature. The reason is that the vapor specific volume decreases with operating temperature increasing. However, as the operating temperature increases, the heat loss of the system and the scale formation rate will increase. Accordingly, we can get the optimal working conditions, that is, the operating temperature of the system is 70°C and the middle concentration is 32%. In Fig. 3, it only shows the second stage of the system in the work when the middle concentration is 20%. This means the process is one stage MVC system. In this case, the compressor power is 75.8 kw and higher than that of the system with two stages working together.

### Experiment, economic and energy analysis:

**Experiment comparison:** In order to verify the simulation results, an experiment is performed in this study. The system flow sheet is shown in Fig. 1 while the view of the system is shown in Fig. 4, which is in service in a factory in Jiangsu, China. The parameters of the experiment are listed in Table 1.

The results in Fig. 5 show the relationship between the total powers of the two compressors and the time. It is clear that the compressor power is undulate with the time. However, an average compressor power can be obtained which is about 83 kw. This value is about 18.9% higher than the simulation result which is 67.3 kw. It is mainly due to the following three facts. First, the heat loss is

neglected when the system is simulated. In fact, a lot of heat is lost in practice. Second, the actual compressor efficiency is low and the non-condensable gas has also increased power consumption. Last, pipeline pressure drop is also neglected when the system is simulated. In fact, it is a negatively effect on the power consumption.

**Economic analysis:** In this part the operating cost and energy saving of the presented system will be compared with the conventional process, such as one stage MVC, single-, two- and three-effect systems. In practice, the total evaporated vapor is about 2000 t/h and the operating time per year is 7200 hours in the presented system. Additionally the steam price in China is 26.5 \$/ton averagely and the electricity price is 0.147 \$/kWh. The energy consumption of one stage MVC system is about 58.6 kwh per ton water in the literature (Dong *et al.*, 2009). The experience value of vapor consumption for evaporating 1ton water is about 1.1, 0.75, 0.4 and 0.3 ton for single-, two- and three-effect systems respectively.

If the conventional single-effect system is used to deal with the wastewater, the running cost (RC1) is:

$$\begin{aligned} RCI &= 2000 \times 7200 \times 1.1 \times 26.5 / 1000 \\ &= 419760 \text{ \$/year} \end{aligned} \quad (1)$$

If the conventional two-effect system is used, the running cost (RC2) is:

$$\begin{aligned} RC2 &= 2000 \times 7200 \times 26.5 / 1000 \\ &= 286200 \text{ \$/year} \end{aligned} \quad (2)$$

In the same way, if the three-effect system is used, the running cost (RC3) is:

$$\begin{aligned} RC3 &= 2000 \times 7200 \times 0.4 \times 26.5 / 1000 \\ &= 152640 \text{ \$/year} \end{aligned} \quad (3)$$

The running cost of one stage MVC system (RCM1) in the literature is:

$$\begin{aligned} RCM &= 2000 \times 7200 \times 58.6 \times 0.147 / 1000 \\ &= 124044 \text{ \$/year} \end{aligned} \quad (4)$$

The running cost of mechanical vapor compression system (RCM2) in this study is:

$$\begin{aligned} RCM2 &= 7200 \times 83 \times 0.147 \\ &= 87847 \text{ \$/year} \end{aligned} \quad (5)$$

Hence, the presented MVC system will save running cost by 79% compared with the single-effect system, 69.3% compared with the two-effect system, 42.4% compared with the three-effect system and 29.2% compared with one stage MVC system.

**Energy saving:** In order to compare the energy consumption of mechanical vapor compression system with that of the conventional system, it is better to convert the steam consumed by conventional system and electricity consumed by the MVC system to standard coal. According to (Dong *et al.*, 2009), 1 kwh electricity and 1 kg are equivalent to about 0.404 and 0.145 kg standard coal, respectively. Thus, the energy consumed by the conventional three- and four-effect system as well as the MVC system is shown below:

$$\begin{aligned} EC3 &= 7200 \times 2000 \times 0.4 \times 0.147 / 1000 \\ &= 835.2 \text{ ton (standard coal) / year} \end{aligned} \quad (6)$$

$$\begin{aligned} EC4 &= 7200 \times 2000 \times 0.3 \times 0.145 / 1000 \\ &= 626.4 \text{ ton (standard coal) / year} \end{aligned} \quad (7)$$

$$\begin{aligned} ECM1 &= 7200 \times 58.6 \times 2 \times 0.404 / 1000 \\ &= 341 \text{ ton (standard coal) / year} \end{aligned} \quad (8)$$

$$\begin{aligned} ECM2 &= 7200 \times 87 \times 0.404 \\ &= 253 \text{ ton (standard coal) / year} \end{aligned} \quad (9)$$

where, EC3 and EC4 are the energy consumed by the three- and four-effect system respectively. ECM1 and ECM2 are the energy consumed by the one stage and new MVC system respectively. From the results, we can see obviously that the new MVC system can save the standard coal by about 69.7, 59.6 and 25.8% compared with the three-effect system, the four-effect system and one stage MVC system respectively.

## CONCLUSION

In this study, a new type of system for recycling ammonium sulfate is proposed. The system consists of two stage MVC systems. The first stage is a forcible recycle evaporator with MVC and the second one is a forcible recycle crystallizer with MVC. The first stage is used to remove part of water and the second stage is used to obtain ammonium sulfate crystals. The system is characterized by simplicity, compactness, ease of operation. All the system is only driven by electric power. The model of the process is built by the ASPEN PLUS software. The simulation results show that the total compressor power of the system is affected by the operating temperature and the middle mass concentration. The compressor power decreases with the operating temperature. The best middle concentration is about 32% and the temperature is 70 .The result is 67.3 kw when the operating temperature is 70 and the middle concentration is 32%.The energy consumption is about 75.8 KW while only one stage MVC system is adopted. An experiment which is used to verify the simulation result of the new system is carried out. The data indicated that the average compressor power is about 83 kw. This system can save running cost by about 29.2% compared with one stage

MVC system. Additionally, it can save running cost by about 79, 69.3 and 42.2% compared with the conventional single-, two- and three-effect systems respectively. Also, it can save standard coal by about 69.7 and 59.6% compared with three- and four-effect system. Outstandingly, it can save standard coal by about 25.8% compared with one stage MVC system.

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