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Analysis on Performance of Screw Compressor in MVR system

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Abstract. Screw compressor is suitable for small scale mechanical vapor recompression (MVR) system especially for the solution with high boiling point elevation. In this paper, a mathematical model of screw compressor in MVR system is built and its working process is simulated. The results show that water injection improves the efficiency of screw compressor obviously and the compression process along saturated vapor line is realized if enough water is injected. The volumetric and isentropic efficiency is not sensitive with the water if more than flow rate of 35L/h is injected. The discharge temperature decreases from 133.4°C to 108°C with water quantities of 5L/h to 35L/h and then it is constant. The large saturated heat transfer difference in evaporator leads to decrement of volumetric efficiency but increment of isentropic efficiency. The mass flow rate of distilled water increase from 0.38t/h to 2.56 t/h and the saturated temperature difference increases from 4°C to 26.9°C when the rotating speed increases from 1000 rpm to 6000rpm.

1. Introduction

Traditional evaporation and concentration process usually use multiple-effect evaporator to finish the separation of solutes from solvents in order to obtain concentrated solution or distilled liquid, such as desalination, wastewater treatment, product concentration. The disadvantage is that plenty of steam is usually consumed because the latent heat of second steam is not completely recovered. A new technique named mechanical vapor recompression is widely used because it reduces the steam consumption. The steam from evaporator in system is compressed by a compressor and then flows into another side of evaporator to heat the feed solution. Only few electricity is required by compressor and some pumps to maintain the operation. More and more multiple-evaporators have been replaced by this system for energy saving, and more studies focus on the further improvement of technical and



economic performance. The analysis of performance influenced by operation parameters is main research point for a mechanical vapor recompression system [1]. The product cost of a single-effect and multi-effect mechanical vapor compression system are also need to be optimized to obtain the suitable input parameters, such as compressor efficiency and the heat transfer area [2-3]. There are some methods of optimized design for mechanical vapor recompression system in order to obtain better comprehensive system performance [4].

Steam compressor is a key equipment for MVR system because it provides the saturated temperature difference in evaporator. It also consumes more power than the pumps in system, such as feed pump, circular pump, distilled water pump and so on. Although roots blower is widely used for small scale MVR system depending on its simple structure and cheap price, the low efficiency also limits its application. Screw compressor is suitable substitute relying on its efficiency and reliability, but there are few studies on steam screw compressor comparing to the refrigeration and air one. An efficient method to analyze the performance influenced by operation parameters, such as suction temperature, pressure ratio and interlope clearance is the simulation of working process by mathematical model [5-7]. The temperature distribution and thermal deformation of rotors are also calculated for some special application to predict the performance accurately and avoid the interference of rotors [8-9]. In order to approaches the isothermal compression process, the water injection is usually adopted for air screw compressor and the results show good improvement for its performance [10].

For the MVR system, relatively small heat transfer temperature difference is reasonable to decrease the power consumption, which means the small pressure ratio is enough for compressor. The oil is forbidden to contaminate the steam and distilled water but water injection is allowed. A screw compressor with water injection provides a choice to improve the performance of this system. It is necessary to analyze the performance of screw compressor in MVR system for optimal design and performance prediction.

2. MVR system and screw compressor

A typical MVR system is shown in Figure 1. The feed solution is preheated in turn by distilled water and no-condensable gas respectively in preheater and cooler, and then it mixes with concentration solution from circular pump. The mixture flows into the tube side of evaporator and is heated by steam in shell side until evaporation. The steam is separated from concentration solution in separator and flows into compressor. The high-pressure steam from compressor flows back to the shell side of evaporator to provide evaporation heat. The distilled water from the shell side of evaporator finishes the preheating process for feed solution in preheater and parts of heat is recovered. At the same time, some no-condensable gas is cooled and pumped out from this system. Some distilled or cooling water is injected into compressor to improve its performance, and the injected water is from distilled water tank or cooling water pipe according to the pressure difference.

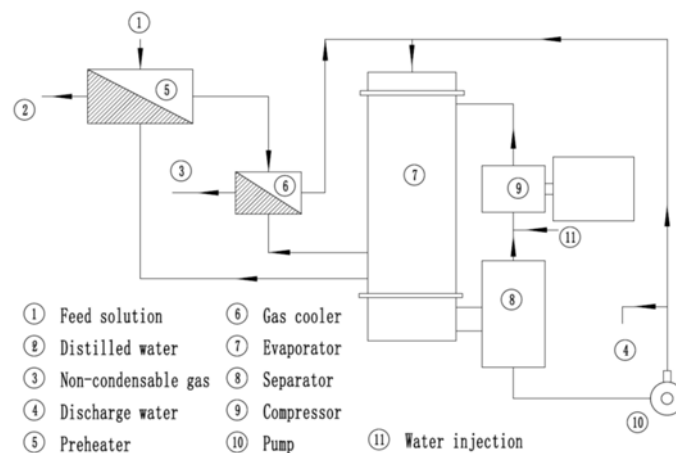


Figure 1. Schematic diagram of MVR system

The screw compressor is consisting of male rotor, female rotor, shell, bearing, seal, motor and other accessories. The volume of chamber is various with the meshing characteristic of rotors to finish the suction, compression and discharge processes. Oil free is required to avoid the contamination of steam but water injection is allowed. The main parameters of screw compressor are shown as Table 1.

Table 1. Parameters of screw compressor

Parameters	Value
Rotor lobe	5/6
Axis-center/mm	195
Length of rotor/mm	425
Diameter of male rotor /mm	273
Diameter of female rotor/mm	218
Area between tooth/mm ²	6643
Inner volume ratio	1.4

3. Theoretical analysis

In order to simplify the water injection process, an assumption is that all the water is injected into suction chamber and mixes sufficiently with the steam from separator. The energy conservation is shown as:

$$m_{ij}h_{ij} + m_{st}h_{st} = (m_{ij} + m_{st})h_{mix}$$

Here, m_{ij} is mass of water injection, h_{ij} is specific enthalpy, m_{st} is mass of steam from separator, h_{mix} is specific enthalpy of mixture.

A chamber of screw compressor is selected as control volume and the energy conservation is described as following equation.

$$\frac{du_{mix}}{d\theta} = \frac{1}{m_{mix}} \left[\sum \left(\frac{dm_{in,mix}}{d\theta} h_{in,mix} \right) + \sum \left(\frac{dm_{out,mix}}{d\theta} h_{out,mix} \right) - \frac{dm_{mix}}{d\theta} u_{mix} - p_{mix} \frac{dV}{d\theta} \right]$$

Here, u_{mix} is internal energy, p_{mix} is pressure, V is volume of chamber, θ is rotation angle, $m_{in,mix}$ is mass of inflow, $m_{out,mix}$ is mass of outflow, $h_{in,mix}$ is specific enthalpy of inflow, $h_{out,mix}$ is specific enthalpy of outflow.

The leakage is inevitable due to the clearances between rotors and shell. It is also a main factor to influence the performance of screw compressor. The leak process is described as following equation:

$$\frac{dm_L}{d\theta} = f_L \frac{A_L}{v_{mix} \omega} \sqrt{\frac{2k_{mix}}{k_{mix}-1} p_{mix} v_{mix} \left(\eta^{\frac{2}{k_{mix}}} - \eta^{\frac{k_{mix}+1}{k_{mix}}} \right)}$$

$$\eta = \begin{cases} \frac{p_{mix,L}}{p_{mix}} & \text{当 } \frac{p_{mix,L}}{p_{mix}} \geq \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} \\ \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} & \text{当 } \frac{p_{mix,L}}{p_{mix}} < \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} \end{cases}$$

Here, m_L is leakage mass, f_L is leakage coefficient, A_L is leakage area, v_{mix} is specific volume of mixture, $p_{mix,L}$ is leakage pressure, k_{mix} is specific heat ratio.

The volumetric efficiency and isentropic efficiency are import parameters to evaluate the performance of compress, and the definitions are shown as:

$$\eta_v = \frac{M_i}{M_a}$$

$$\eta_s = \frac{W_i}{W_a}$$

Here, η_v is volumetric efficiency, η_s is isentropic efficiency, M_i is mass flow rate for ideal compression process, M_a is mass flow rate for actual compression process, W_i is power for isentropic process, W_a is power for actual process.

For the MVR system, the mass flow rate of distilled water is decided by the mass flow rate of compressor and it of injection water.

$$M_{dis} = M_a - M_{ij}$$

The calculation process of simulation model by c++ program is shown in Figure 2. The ideal compression process is used as the initial values for the actual process. The calculation is finished if the pressure difference for same rotation angle with different iteration numbers is small enough.

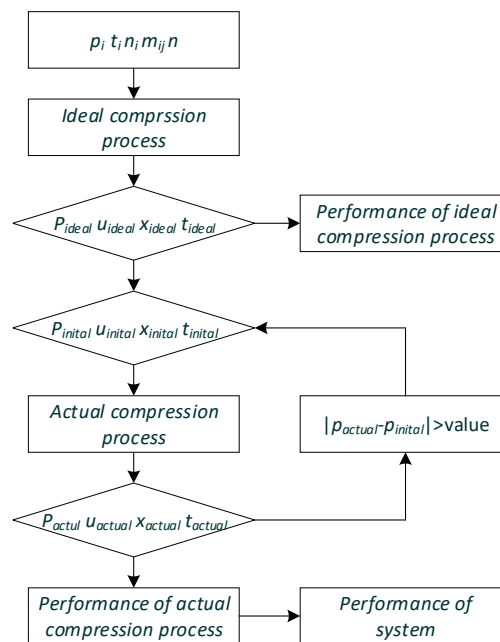


Figure 2. Calculation process of simulation model

4. Results and discussion

The p-V diagram with different volume flow rate of water injection is shown in Figure 3 when rotating speed is 3000rpm, suction temperature is 95°C, discharge pressure is 135kPa, and temperature of water is 50°C. The obvious cooling effect is shown when some water is injected. For the large flow rate of water injection condition, the temperature of vapor in chamber is closer to the saturation state. The compression process is finished nearly along the saturated vapor line if the water injection is large enough. The power consumption also decreases due to the small area formed by p-V curve, which is the advantages of water injection.

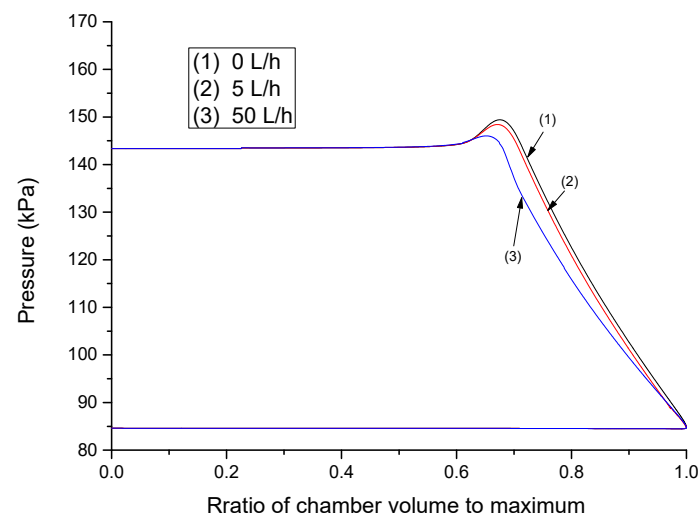


Figure 3. p - V diagram of screw compressor

The volumetric and isentropic efficiencies influenced by volume flow rate of water injection is shown in Figure 4. For the vapor with high degree of superheat, the water injection has good cooling effect and makes the vapor temperature close to the saturated temperature. If the vapor is saturated, the temperature is constant even if injecting more water. The volumetric and isentropic efficiency increase when the volume flow rate of water injection is small but then vary slightly. This means that the efficiency is not sensitive after this critical value for water injection. Under the simulation condition, the value is 35 L/h and the corresponding volumetric and isentropic efficiency are 95.5% and 87.9%.

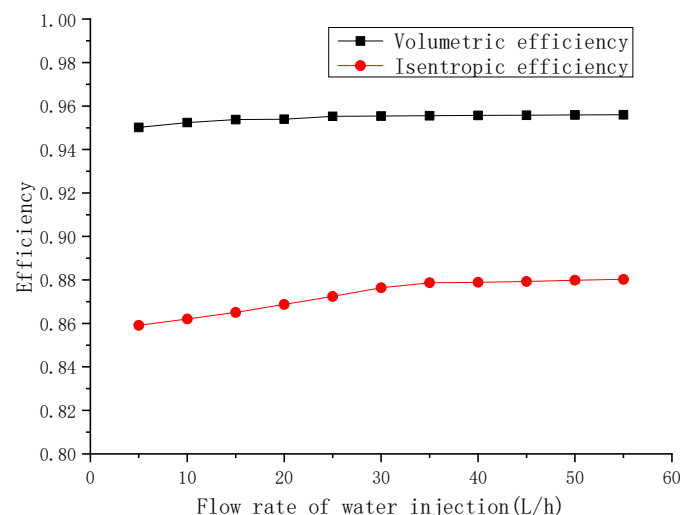


Figure 4. Volumetric and isentropic efficiency with water injection

The various of discharge temperature with volume flow rate of water injection are shown in Figure 5. The discharge temperature is high if no water is injected into chamber, but it decreases with the quantities of water injection until the vapor is saturated. Then the discharge temperature is constant even if increasing the water. The discharge temperature decrease from 133.4°C to 108°C when 5 L/h and 35 L/h of water is injected under the calculated condition. If increasing the volume flow rate of water from 35 L/h to 55 L/h, the discharge temperature is constant, which means the vapor from outlet

reaches saturated state. The power of compressor per ton of distilled water also decreases with the flow rate of water injection firstly and then it changes slightly because the efficient compression process. It decrease from 31.5kWh/t to 30.2kWh/t when the injected water increases from 5L/h to 35L/h, and then it is nearly constant.

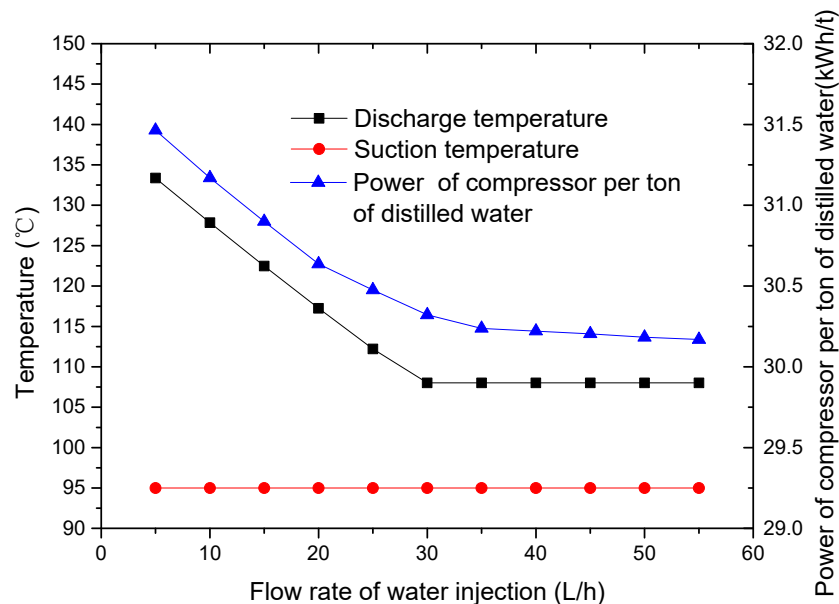


Figure 5. Temperature and power consumption with water injection

The variation of efficiency with rotating speed is shown in Figure 6. The leakage loss decreases with the rotating speed, but the suction and discharge loss increase at the same time. Hence, the volumetric efficiency and isentropic efficiency increases with rotating speed but they become smoother under the high rotating speed condition. smaller leakage loss through clearance and larger flow loss through suction and discharge port, the volumetric and isentropic efficiency increase with the rotating speed under the calculated condition. But the variation of efficiency become smooth gradually when the rotating speed is high. Seal, bearing and motor limit the infinite increment of rotating speed.

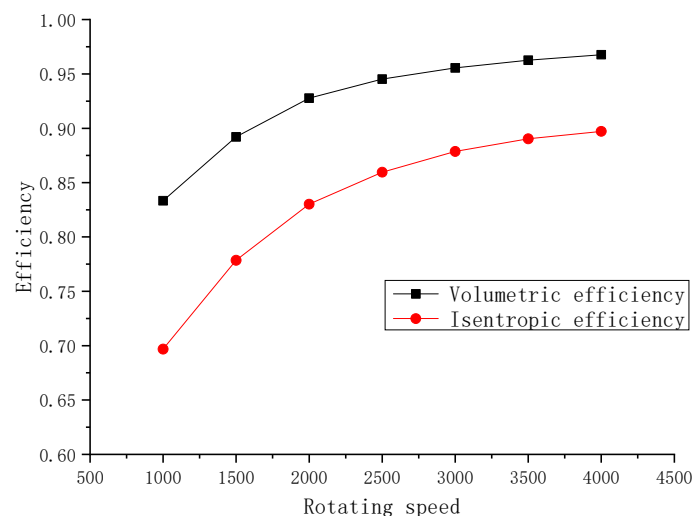


Figure 6. Efficiency with rotating speed

For the solution with high elevation of boiling point, high heat transfer temperature difference is needed. The variation of efficiency with condensation temperature is shown in Figure 7. The high condensation temperature requires high discharge pressure of compressor and it influences the volumetric and isentropic efficiency. Because the leakage is decided by the channel area and pressure difference, the volumetric efficiency decreases with the condensation temperature. The unmatched pressure ratio to discharge area leads to the over compression and under compression, which influences the isentropic efficiency. The isentropic efficiency increases with the condensation but the variation decreases gradually. The power consumption of compressor for per ton of distilled water is usually used to evaluate the performance of MVR system. The apparent increasement means more power is consumed for the solution with high elevation of boiling point.

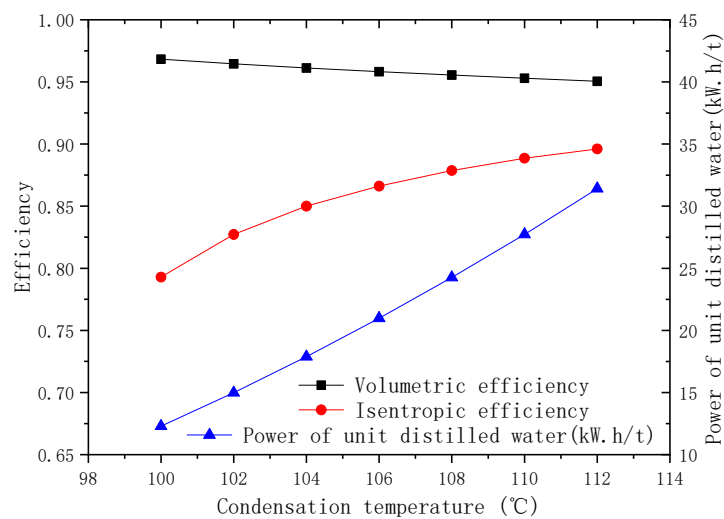


Figure 7. Efficiency and power consumption with condensation temperature

The variation of saturated temperature difference and mass flow rate of distilled water with rotating speed is shown in Figure 8. For the MVR system with screw compressor, rotating speed regulation is an effective way to change the operating condition. The evaporation temperature is usually controlled as constant, and the mass flow rate of vapor from evaporator increases with the rotating speed, which increases the thermal load of evaporator. It needs larger heat transfer difference in evaporator to provide the large heat flux due to the nearly constant heat transfer coefficient. The heat transfer temperature difference increases inevitably in order to finish the evaporation process and a new working condition is built. The mass flow rate of distilled water increases from 0.38t/h to 2.56 t/h and the saturated temperature difference increases from 4°C to 26.9°C with the rotating speed increasing from 1000 rpm to 6000rpm. Comparing to the surge phenomenon of centrifugal compressor, the MVR system with screw compressor has widely regulation range.

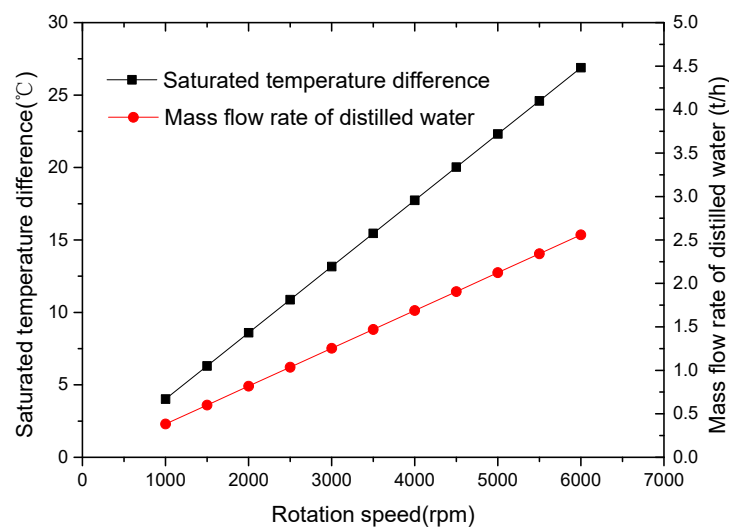


Figure 8. System performance with rotating speed

5. Conclusion

The performance of screw compressor is improved obviously by water injection and the compression process is finished nearly along the saturated vapor line if the injected water is enough. A critical flow rate of water injection determines whether the vapor in chamber is saturated. The volumetric and isentropic efficiency is not sensitive if larger than 35L/h of water is injected, and the volumetric and isentropic efficiency are 95.5% and 87.9% at this point. The discharge temperature also decreases from 133.4°C to 108°C when 5L/h and 35L/h of water is injected. The large saturated heat transfer difference in evaporator leads to the decrement of volumetric efficiency but increment of isentropic efficiency. The rotating speed is an effective regulation parameter of system and the volumetric and isentropic efficiency increase with it. The mass flow rate of distilled water increase from 0.38t/h to 2.56 t/h and the saturated temperature difference increases from 4°C to 26.9°C when the rotation speed increases from 1000 rpm to 6000rpm.

Acknowledgements

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