Research on Energy Saving Optimization of MVR Distilled Water Machine

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Abstract: Compared with the multi-effect distilled water machine, the mechanical vapor recompression (MVR) distilled water machine has many advantages, and has been a trend to replace the traditional distilled water machine. Based on the conservation equations of mass and energy, this paper designs an MVR distilled water production process and establishes the corresponding thermodynamic model. Effects of the produced water temperature, heat exchange temperature difference, compressor adiabatic efficiency, and pipeline loss to the produced water energy consumption, energy saving rate and coefficient of performance (COP) were studied. Research shows that the MVR distilled water machine is more suitable for occasions with low water production temperature. Appropriate heat exchangers and compressors should be selected to improve comprehensive performance through heat exchange temperature differences and improving adiabatic efficiency.

Key words: Distilled water, mechanical vapor recompression (MVR), heat pump, energy saving.

1. Introduction

In the pharmaceutical industry, the water used in the pharmaceutical production process is mainly drinking water, water for injection, purified water, and sterile water for injection. Among them, water for injection is often used to dissolve or dilute injection drugs or preparations, etc., and is used in large quantities in the production of drugs [1]. The current methods of preparing water for injection are: ion exchange method, electrodialysis method, reverse osmosis method, ultrafiltration method and distillation method [2-7]. The ion exchange method does not involve phase change, has no moving equipment, is low-cost and can remove pyrogen. As it cannot reduce the density of bacteria, it generally needs to be designed and used in conjunction with other process methods. Electrodialysis method has low energy consumption, low environmental pollution, simple operation and high-water utilization rate. It is generally used as a water pretreatment method for production process [8]. The reverse osmosis method and ultrafiltration method are usually used in combination. Ultrafiltration pretreats the feed water to extend the service life of the reverse osmosis membrane, but it still cannot meet the requirements for water for injection. The 2010 edition of the Chinese Pharmacopoeia stipulates that water for injection must be prepared by distillation [9].

Using Multi-Effect distillation (MED) to prepare water for injection is still the most widely used method at present. Its technology is mature and there is no sports equipment. The distilled water produced meets the current US, European, Japanese and Chinese Pharmacopoeia about injection water requirements [10, 11]. However, there are still some problems with the MED water machine, such as the large number of heat exchangers, large area, low degree of equipment automation, high operating pressure and temperature, especially in order to reduce steam consumption, it is necessary to increase the efficiency and further enlarge the above problems.

With the rise of coal and steam prices and relatively stable electricity prices, coupled with the country’s
emphasis on environmental protection issues, the process of using heat pump technology to evaporate materials has become increasingly popular in various industries. This technology is often called mechanical steam recompression (MVR—Mechanical Vapor Recompression) [12]. And in the fields of distilled water production and seawater desalination, it is usually called “Hot Pressure Distillation” (VCD—Vapor-Compression Distillation) [13]. The so-called VCD water machine is to compress the secondary steam generated by distillation to increase the saturation temperature and reuse it. It only needs to add a certain amount of compression work and a small amount of heat to achieve the purpose of evaporation of materials [14, 15]. Compared to MED, the main advantages of VCD are:

1. High energy-saving potential: The steam consumption of MED water machine is related to the efficiency, which is limited by the cost of equipment, control complexity, and cooling water temperature. Most of the efficiency is less than 7, and the most commonly used is 4 effects. The primary energy utilization coefficient is higher than the eight-effect MED water machine;

2. Simple equipment: VCD water machine is equivalent to a single-effect MED water machine plus a compressor, the number of heat exchangers is greatly reduced, and a large amount of cooling water is not required to maintain back pressure during normal operation, and there are fewer supporting public works;

3. Other advantages: The VC system has a small footprint and high degree of automation. As the main energy source comes from electrical energy, its carbon emissions are small, and the cleanliness is higher when producing Medical distilled water, and non-pressure equipment has low qualification requirements for production and installation.

Foreign companies such as Aqua-chem, Meco, StilMas, BRAM-COR, etc. have been selling VC water machines all over the world since the last century, and have achieved good energy-saving effects. Many companies in China have also developed VC water machines in recent years, but there is still a certain gap compared with foreign products.

Comparison of VCD and MED water machines under different water production rates and different water production temperatures was shown in Fig. 1. It can be seen that the operating cost of VCD is significantly lower than that of MED, but it can be found that the higher the temperature of the final distilled water product, the lower the energy saving.
benefit. In addition, comparing the unit water production steam consumption of Aqua-chem Company and BRAM-COR Company, it is found that the two are very different, the former is about 0.104 T (steam)/T (distilled water), and the latter reaches 0.15 T (steam)/T (distilled water). The reason is that the two processes are different, especially different compressor types.

At present, VCD water machines at home and abroad mostly focused on product introduction, process analysis, or direct energy saving benefits without detailed theoretical analysis. In view of this, this article establishes VCD on the premise of reasonable assumptions. The thermodynamic model of the water machine analyzes the effects of production temperature, compressor adiabatic efficiency, evaporation-condensation heat exchange temperature difference, inlet and exhaust pressure loss on cop and energy saving benefits.

2. VCD Water Machine Mathematical Model

2.1 VCD Water Machine Process

Fig. 2 is a schematic diagram of the working process of a VCD water machine, and Fig. 3 is a Ts diagram. As it can be seen from Figs. 2 and 3, the low-temperature raw water 1 treated by filtering reverse osmosis and the like is first exchanged with distilled water 6 from the inside of the main heat exchanger HEX4 for heat recovery. Heat exchanger HEX1 exchanges heat, the temperature of the raw water rises to 2 points, and the temperature drops to 9 points to reach the desired temperature of the distilled product water. Then the raw water is further preheated by steam in the preheater HEX2 to reach the saturated state 3. The saturated water at the bottom of the tower after being pumped by the circulating pump, then sprayed down from the water distributor and evaporates on the surface of HEX4 in order to forming the secondary steam. The secondary steam is pressurized by the compressor and enters HEX4 and releases heat to evaporate the spray water of HEX4. A heat exchanger HEX3, which is supplemented by primary steam, is placed at the bottom of the still to supplement the insufficient heat inside the main heat exchanger HEX4.

2.2 Basic Assumptions

In order to simplify the difficulty of the mathematical model, some unimportant factors are omitted, and the following reasonable assumptions are made:

(1) Regardless of the sewage discharge process, the flow of raw water and distilled water is the same;
(2) No consideration of heat loss, no consideration of flow resistance;
(3) Regardless of the heat exchanger efficiency, only the heat exchange amount is calculated according to the enthalpy equilibrium relationship;
(4) Mechanical efficiency and motor efficiency are 90%; electricity cost is 1 yuan/kWh, steam price is 240 yuan/ton; primary steam pressure is 0.3 MPag, primary steam inlet is saturated steam, and outlet is saturated water;
(5) The power consumption of the pump and the cost of condensate are ignored in the calculation;
(6) The MED water machine selected a company’s six-effect water machine and believed that its steam consumption was fixed.

2.3 Mathematical Description

HEX1 to HEX4 heat exchange capacity and compressor power consumption are:

\[ Q_1 = \dot{m}_w (h_2 - h_3) = \dot{m}_w (h_7 - h_8) \]  \hspace{1cm} (1)

\[ Q_2 = \dot{m}_w (h_3 - h_2) = \dot{m}_w (h_6 - h_7) \]  \hspace{1cm} (2)

\[ Q_3 = \dot{m}_w (h_8 - h_5) \]  \hspace{1cm} (3)

\[ Q_4 = \dot{m}_w (h_9 - h_8) \]  \hspace{1cm} (4)

\[ W = \dot{m}_w (h_4 - h_5) = \dot{m}_w \left( \frac{h_9 - h_5}{\eta_c} \right) \]  \hspace{1cm} (5)
Fig. 2  Schematic diagram of the VCD water machine process.

Fig. 3  VCD water machine temperature entropy diagram.
Where \( \dot{m}_w \) is the mass flow of raw water, \( \dot{m}_{2} \) and \( \dot{m}_{3} \) is the flow of primary steam in HEX2 and HEX3, \( h_3 \) is the enthalpy value after isentropic compression, \( \eta_c \) is the adiabatic efficiency of the compressor, and the other is the enthalpy value at each point.

According to the energy conservation relationship, it can be obtained that the relationship between the heat exchange capacity of HEX3 and the heat exchange capacity of other heat exchangers is:

\[
Q_3 = \dot{m}_w (h_4 - h_2) - Q_2 - Q_4 \tag{6}
\]

According to Eqs. (1-6), the enthalpy, heat exchange capacity and the power consumption of the compressor can be obtained as long as the water flow rate, the distilled product water temperature and the isentropic efficiency of the compressor.

The coefficients of performance of the heat pump and the system are Eqs. (7) and (8).

\[
COP_e = \frac{\dot{Q}_e}{\dot{W}} = \frac{h_4 - h_2}{h_4 - h_5} \tag{7}
\]

\[
COP_s = \frac{\dot{m}_w (h_4 - h_2)}{\dot{W} + \dot{Q}_2 + \dot{Q}_3} \tag{8}
\]

To define the energy saving rate:

\[
\varepsilon = \frac{M_{MED} - M_{VCD}}{M_{MED}} \tag{9}
\]

In Eq. (9), \( M_{MED} \) and \( M_{VCD} \) are the energy consumption costs per ton of water produced by the MED water machine and the VCD water machine, respectively.

### 3. VCD Water Machine Performance Analysis

#### 3.1 Energy Saving Comparison of MED and VCD Water Machine

Table 1 gives the calculation results of the VCD water

| Parameter                              | Value   | Unit  |
|----------------------------------------|---------|-------|
| Raw water temperature                  | 25      | °C    |
| Distillation temperature difference (HEX4) | 5       | °C    |
| Evaporation temperature outside the tube \( t_i \) | 100     | °C    |
| Condensing temperature in the tube \( t_6 \) | 105     | °C    |
| Distilled water outlet temperature \( t_7 \) | 92      | °C    |
| Condensing pressure                    | 0.12    | MPa   |
| Evaporation pressure                   | 0.10    | MPa   |
| Compressor inlet temperature           | 105     | °C    |
| Compressor outlet temperature           | 126.2   | °C    |
| Compressor pressure ratio              | 1.19    |       |
| Compressor power                       | 14.1    | kW    |
| Compressor Displacement (Inlet)        | 28.3    | m³/min|
| Heat required for raw water evaporation | 714.1   | kW    |
| Heat from heat pump                    | 650.4   | kW    |
| Primary steam needs heat               | 63.6    | kW    |
| Power consumption                      | 14.1    | kW.h  |
| Amount of steam to be replenished      | 0.107   | T/h   |
| Compressor electricity costs           | 11.3    | yuan  |
| Steam cost                             | 23.6    | yuan  |
| Total cost of produced water per ton   | 34.9    | yuan  |
| A company MED once the amount of steam | 0.22    | T/h   |
| A company MED once steam fee           | 48.4    | yuan  |
| VCD water machine ton water saving     | 13.5    | yuan  |
| Energy saving efficiency               | 27.9    | %     |
machine with a water production capacity of 1 T/h under the rated design conditions, and compares it with the six-effect MED water machine of a company. It can be seen from the calculation results that the steam consumption per ton of water production is reduced by about 50%, but the compressor consumes electrical power. So, the actual energy saving benefit is only about 20%. MED is the actual measurement data, and VCD is the ideal calculation value. If you consider the actual factors such as system heat loss, the energy saving rate is expected to be about 15%.

3.2 Effect of Water Temperature on System Performance

Fig. 4 shows the relationship between the temperature of the produced water and the electricity consumption of the compressor, the cost of the primary steam, and the cost savings. It can be seen that as the temperature of the produced water increases, the electricity cost of the compressor remains the same, but the latent heat of the steam is different at different pressures. The secondary steam boosted by the compressor cannot evaporate the same flow of raw water, and a certain amount of secondary steam needs to be evaporated by HEX3 to maintain the material balance. So, the cost of the primary steam increases linearly. Especially the inlet temperature of the raw water is only 25 °C. The saturation temperature is 100 °C far away, so additional heat is required. If the temperature of the product’s distilled water is low, the heat of the high-temperature distilled water from the HEX4 outlet can be recovered to raise the temperature of the raw water. However, if the distilled water temperature is high, an additional primary steam is required to raise the temperature of the raw water.

It can also be seen from Fig. 4 that when the temperature of the product’s distilled water is lower than about 70 °C, the energy cost of one steam is lower than the electricity cost of the compressor, but when it is higher than 70 °C, the energy cost of one steam is higher than the electricity cost. When the temperature of distilled water is 40 °C, there is no need to replenish the steam, and the energy saving benefit is very high. Therefore, it can be found from the calculation that the VCD water machine is more suitable for occasions where the temperature of the distilled water of the product is lower.

3.3 Effect of HEX4 Heat Transfer Temperature Difference on System Performance

Fig. 5 shows the effect of the heat exchange temperature difference between the inside and outside of the HEX4 tube on the energy saving efficiency of the VCD water machine when the product’s distilled water temperature is 92 °C. As it can be seen from
Fig. 5 Effect of evaporation-condensation heat transfer temperature difference on VCD water machine.

Fig. 5, the VCD water machine is very sensitive to the heat exchange temperature difference. As the pressure ratio increases, the required power also increases, and the energy consumption increases linearly. This is consistent with the conclusions in other heat pump evaporation systems, that is, if the design conditions allow, the heat exchange temperature difference should be minimized to reduce the power consumption of the compressor to improve the coefficient of performance of the system.

3.4 Impact of Compressor Adiabatic Efficiency on System Performance

Fig. 6 shows the impact of the adiabatic efficiency of the compressor on the VCD water machine. From Fig. 6, it can be seen that the lower the adiabatic efficiency, the greater the power consumption of the compressor. However, as the adiabatic efficiency reflects factors such as wear and friction in the compressor, and these friction losses are always converted into heat and taken away by the compressor exhaust, which is ultimately used to evaporate the raw water, the amount of steam at one time will be slightly reduced. The reduction is not as much as the increase in the power consumption of the compressor, so the overall energy saving benefit is reduced. However, compared with Figs. 5 and 6, the adiabatic efficiency of the compressor has little effect on the VCD water machine.
3.5 Impact of pressure loss on energy saving rate

Fig. 7 shows the effect of inlet and exhaust pressure loss on the energy saving rate. It can be seen that for each increase of inlet and exhaust pressure loss, the energy saving rate will decrease by 1%. Because the compressor exhaust pressure is much higher than the intake pressure, the impact of intake loss is greater. The size of the intake pipe should be increased to reduce the distance.

4. Conclusions

By establishing a thermodynamic model of a VCD water machine, the effects of several key parameters on the system performance were quantitatively studied. The research results show that:

Under the design conditions selected in this article, compared to the six-effect MED water machine, the VCD water machine has a good energy saving effect; however, when the temperature rises, the VCD water machine’s energy saving rate will gradually decrease. So, the VCD water machine is more suitable for use in occasions where the temperature is low;

The temperature difference of the main condensation-evaporation heat exchanger has a great impact on the performance. As the temperature difference decreases, the energy saving rate of the VCD water machine increases. So, choosing a heat exchanger such as a horizontal pipe falling film can improve the performance of the VCD water machine. Thermal efficiency also affects the performance of VCD water machines. So, the use of centrifugal compressors with high adiabatic efficiency is also beneficial to VCD water machines; reducing the intake and exhaust loss can also improve the performance of VCD water machines, and the impact of air intake loss is greater than the exhaust loss.

The mathematical model established in the study only considers the temperature difference of the main condensation-evaporation heat exchanger HEX4, but does not consider the temperature difference of other heat exchangers. At the same time, the MED water machine model is not established, but the actual parameters of the manufacturer are directly selected. Further research will be carried out in the future.

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