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Experimental research on MVR system for industrial wastewater treatment

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ABSTRACT

Mechanical vapor recompression system is an energy-saving system for saline effluent treatment because nearly no external steam is required in the system. The combination of centrifugal compressor and falling film evaporator is more suitable for the large-scale industrial system. An experimental system is developed and tested in this paper. The results show that the treatment capacity of distilled water is 0.88–1.24 and 0.77–1.15 t h^{-1} with rotating speeds of compressor of 20,000 and 19,500 rpm, respectively. The compressor consumes about 3.1–4 kW shaft power if saturated temperature difference increases 1°C, and 24.8–28.7 kWh is consumed when 1 t distilled water is recycled. The compressor runs reliably, and the maximum shaft vibration amplitudes of compressor and motor are 12 and 19 μm, respectively. The average mass flow rates of feed water, discharge water, and distilled water are 1.07, 0.15, and 0.93 t h^{-1} in continuous 24 h experiment time. The power consumptions of compressor, vacuum pump, circulation pump, and distilled water pump are 75.9%, 10.4%, 4.1%, and 2.9% for the whole system. The maximum total dissolved solids of discharge and distilled water are 78,650 and 118 mg L^{-1}, respectively, and the maximum concentration ratio is 18.7 for the tested water samples.

Keywords: MVR; Treatment capacity; Power consumption; TDS

1. Introduction

Saline effluent is inevitable in oil production, chemical industry, metal smelting, electroplating, and other fields. The new treatment method of saline effluent is imperative because traditional disposals are harmful to the environment, such as evaporation ponds, deep wells, and coastal discharge. Zero-emission is the development trend for industrial wastewater treatment by which there is no sewage water discharged and only solid waste is processed. Usually, desalination by membrane separation technique is the main method owing to its performance and economic efficiency, such as forward osmosis [1–3], membrane distillation [4–6], reverse osmosis [7], and nanofiltration [8]. Recovering water by evaporation is also used in many plants because it can obtain more clean water, more cheaper equipment cost, and larger concentration ratio, such as multiple-effect desalination system [9]. Owing to different resistance to organic and inorganic fouling for forward osmosis, membrane distillation, and reverse osmosis [10], their applications are limited especially for the large concentration condition. Some hybrid systems coupling with two or more techniques are developed to increase the amount of extracted salt and reduce the final volume of rejected brine, such as the nanofiltration (pretreatment)–reverse osmosis (concentration)–thermal processes (crystallization) [11]. A modified evaporation system named mechanical vapor recompression (MVR) system shows excellent performance for waste with high salinity, which realizes further concentration for the drainage of membrane system and only consumes less electrical power at the same time.

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The essential distinction between MVR and multi-effect evaporation system is that the former utilizes latent heat from the second steam to evaporate feed water and the external steam is nearly unnecessary except preheating process before start-up. A steam compressor in MVR system is used to elevate the saturated pressure of steam from separator to form heat transfer temperature difference in evaporator. With evaporation of feed water and condensation of second steam, the clean water is separated and recycled.

The performance analysis and evaluation of MVR system are very important for design and operation regulation, which promotes a large research to focus on the feasibility evaluation, thermo-economic analysis, and exergo-economic analysis of this system. The single-stage and multistage MVR system is proposed by Han et al. [12] to concentrate solution with high salinity and availability to achieve the aim of zero-emission. In order to avoid electricity shortage in many occasions, an organic Rankine cycle is coupled to drive the steam compressor of mechanical vapor compression desalination system by He et al. [13], and the integration system is distinctly feasible to fulfill the freshwater production. A thermo-economic and exergo-economic analyses of single-effect and multi-effect MVR desalination systems are investigated, respectively, to estimate their performances by Jamil et al. [14–16], and the power consumption, exergy destruction, efficiency, heat transfer area, and product cost are analyzed under various conditions in order to optimize design and operation parameters. An experimental unit of capacity of 20 kg h^{-1} for high-salinity wastewater with Na_2SO_4 is provided by Yasu et al. [17], by which the effect of parameters on power consumption and heat transfer area is analyzed. A single-effect MVR system for concentrating dimethylacetamide wastewater is investigated by Yulong et al. [18], and the rate of distilled water production is 70.80 kg h^{-1} at the operating condition of atmospheric pressure, but it is only 18.2 kg h^{-1} at the evaporation temperature of 55.8°C. The mechanical vapor system is processed by Zhilong et al. [19] to treat landfill leachate, and full-scale experiments indicate its adaptation to the drastic changes of pollutant concentrations. Because the heat transfer temperature difference in evaporator is provided by compressor, improving the performance of compressor is very important for this system. For most of wastewater, the high pressure ratio is not necessary but oil-free compression is essential. Centrifugal compressor is the main typical type for the large-scale system, while root blower and screw compressor are more suitable for small-scale system. An effective method to improve the performance of screw compressor is water injection technology because the approximate isothermal compression process is realized. The *p*–*V* indicator diagrams of a twin-screw compressor are recorded by Yafen et al. [20], and the predictive improvements of volumetric efficiency and adiabatic indication efficiency are 5% and 6%, respectively. An experimental study on twin-screw compressor for a 50-m^3 d^{-1} double-effect MVR system from Jiubing et al. [21] also shows similar conclusions. The single-screw compressor is also used for MVR system by Junling et al. [22], and the experimental results show that the superheat can be eliminated by injecting distilled water. Although centrifugal compressor is relatively reliable due to its less motion parts, the impeller damage still exists because of unreasonable design and operation [23,24], which means more optimizing design and reasonable regulation are very important compared with the displacement type of compressor structure.

Above all, most of the researches for MVR system still take theoretical analysis method to simulate the performance even if few remaining experimental investigations also use displacement compressor because of the small-scale laboratory prototype. The distinct difference in operation characteristic between volumetric and centrifugal compressors decides some results are not universal for different types of systems. Study on the device combining centrifugal compressor and falling film evaporator is insufficient although it is more similar to an industrial one. In this paper, an experimental system for industrial wastewater is developed, and its performance is tested in a chemical plant. The evaluation of system performance is worth of reference for a magnified industrial system.

2. Experimental system

An experimental MVR system for coal chemical wastewater is developed, which includes preheater, falling film evaporator, centrifugal compressor, separator, circulation pump, feed pump, distilled water tank, vacuum pump, and other devices (Fig. 1). The wastewater comes from a sewage pool of chemical plant, and a pretreatment system is added before MVR system in order to remove suspended solid and part of Ca^+ and Mg^+ and to reduce the load of MVR system because the drainage with saline from pretreatment is further concentrated in the MVR system. The feed water from pretreatment system flows into preheater first and then goes into tube side of the evaporator. After evaporation, the steam is separated from mixture in separator and then flows into the compressor. Pressured steam by compressor is transported into the shell side of the evaporator to heat feed water, and the distilled water is generated at the same time. A vacuum pump is necessary to draw the noncondensation from the system and maintain the operation pressure of system.

The MVR system including a centrifugal compressor and a falling film evaporator is an integral construction, whose design treatment capacity is 1 t h^{-1} (Fig. 2). A gear accelerator is used to increase the rotating speed of the compressor, and a special seal is adopted to ensure oil free of compression process. All the heat exchangers, separator, tanks, and tubes are insulated to reduce the heat loss. A programmable logic controller is used to monitor and regulate the operating conditions. Some pressure, temperature, flow rate, and vibration sensors are installed in the special points to measure the parameters of steam and water. Before start-up, external steam flows into the evaporator through a valve for preheating the feed water until its temperature is close to the operation point. The system parameters start to be regulated automatically when the operation is switched to automatic mode. Some external steam is still needed after the preheating process to supplement the heat loss of equipment and pipes.

3. Results and discussions

The experimental system is designed to recycle the coal chemical wastewater in a chemical plant, and its design parameters are shown in Table 1. The performances of the system are tested, and some analysis is as follows.

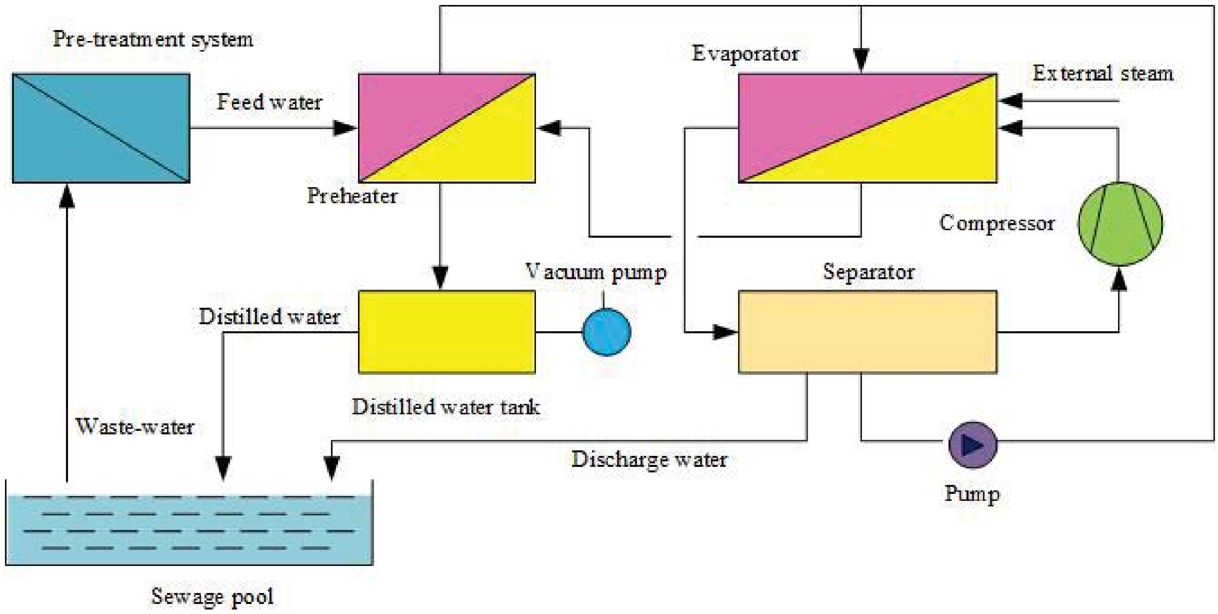

Fig. 1. Schematic of experimental system.

Fig. 2. Experimental MVR system.

The performance curve of the compressor with different rotating speeds is shown in Fig. 3, in which the pressure ratio varies with mass flow rate. It also reflects the relationship between treatment capacity of system and heat transfer temperature difference in evaporator. Larger pressure ratio means small mass flow rate at same rotating speed for a centrifugal compressor unless the surge condition occurs. The mass flow rate changes from 0.88 to 1.24 t h^{-1} with

Table 1
Design parameters of experimental system

Items	Parameters
Structure type	skid mounted
Compressor	Centrifugal
Evaporator	Falling film
Treatment capacity (t h^{-1})	1
Evaporation (°C)	70
Saturated temperature difference (°C)	10

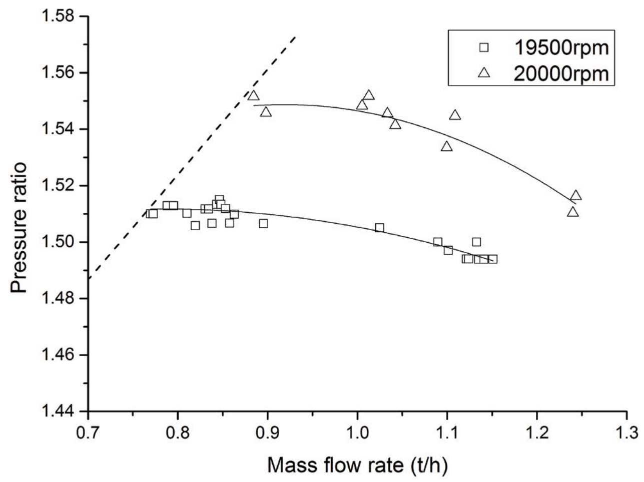

Fig. 3. Performance curve of compressor.

rotating speed of 20,000 rpm and the values are 0.77 and 1.15 t h^{-1} when the rotating speed is 19,500 rpm, although there is a small variation of pressure ratio. Thus, the compressor shows large adjustment range for the design point with different rotating speeds. The imaginary line shows the minimum mass flow rate with different rotating speeds, which is named surge line. If the mass flow rate of vapor is less than this line caused by high concentration of solution, foam in separator, leakage, and so on, the system must be shut off.

The steam compressor provides temperature difference of heat transfer in evaporator, and it is a main power consumption device for this system. The saturated temperature difference is usually used to evaluate the performance of compressor (Fig. 4). The shaft power consumption of compressor increases with saturated temperature difference due to the increasing pressure ratio, and the variation is 25.8–34.5 kW. It can be seen from Fig. 4 that the compressor consumes about 3.1–4 kW shaft power as saturated temperature difference increases 1°C. For some special solution or operating condition, high saturated temperature difference is necessary if the object discharge water has high boiling point elevation, which means the inevitable larger power consumption of compressor is required.

The shaft vibration is an important factor to monitor and evaluate the reliability of compressor (Fig. 5). For the gear accelerator, a high rotating speed axis is used to drive compressor and the low rotating speed is connected to motor.

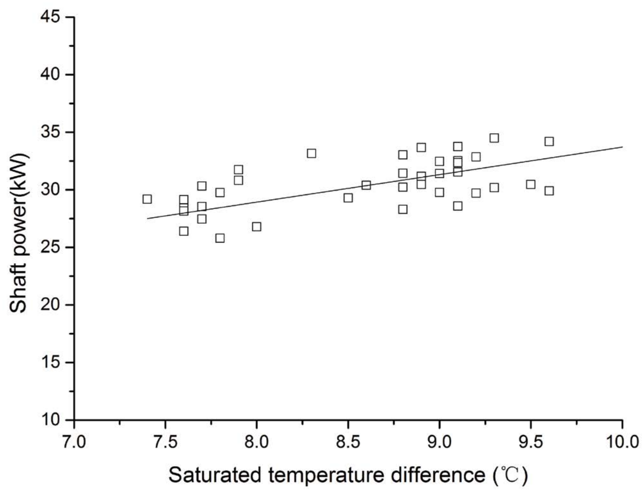

Fig. 4. Shaft power of compressor with saturated temperature difference.

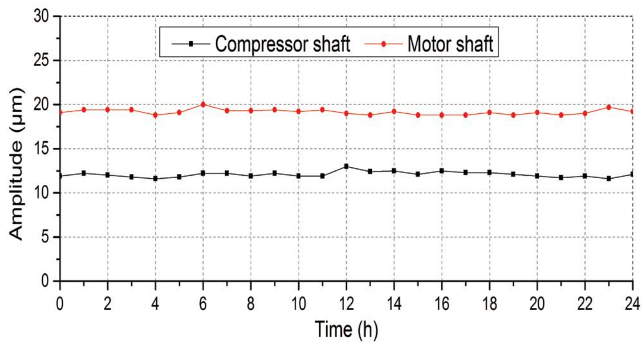

Fig. 5. Shaft vibration of compressor and motor.

The low amplitude of shaft vibration depends on the excellent dynamic balance if the operation point is not near to the critical speed. The vibration amplitudes of compressor and motor shaft are 12 and 19 μm, respectively, when the rotating speed is 19,500 rpm of compressor and 2,786 rpm of motor, which meet the criterion of API617. It should be emphasized that the vibration of high rotating speed shaft deserves more concern because it influences the safety of impeller directly.

The treatment capacity of system under automatic mode is shown in Fig. 6. Although only the continuous data in 24-h

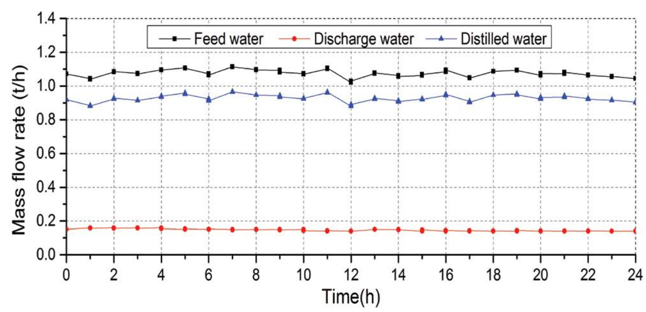

Fig. 6. Treatment capacity of system.

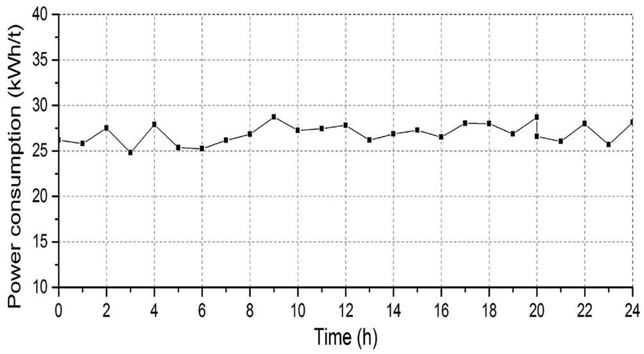

Fig. 7. Power consumption of system.

operation are provided, there is no failure for the compressor and system for more than 30 d experiment time. The average mass flow rates of feed water, discharge water, and distilled water are 1.07, 0.15, and 0.93 t h^{-1}, respectively, on the test conditions. The system realizes 7.1 times concentration process for the feed water, and 86.9% of feed water is recycled. The water flow is stable in the tested time, and the maximum fluctuations of feed water, discharge water, and distilled water are within ±4.9%, ±6.4%, and ±5%. It also shows that the control system is reliable to maintain the operating parameters by regulating valve opening and rotating speed of pump.

The shaft power of compressor per unit distilled water in continuous 24 h is shown in Fig. 7. It is a significant foundation to predict the performance of a similar large-scale system. Under automatic regulation conditions, compressor consumes shaft power of 24.8–28.7 kWh when 1 t distilled water is recycled, and the maximum fluctuation is within ±7.8% compared with the average value of 26.9 kWh. It is more economical compared with the multi-effect evaporation system with respect to the price of electricity and external steam.

The distribution of power consumption for experimental system is shown in Fig. 8, as the rotating speed is 20,000 rpm. The power of 75.9% consumed by compressor builds the heat transfer temperature difference in evaporator, the power of 10.4% used by vacuum pump keeps the noncondensation gas out from evaporator, and the power of 4.1% taken by circulation pump increases the flow rate of each tube in evaporator and avoids the dry-tube phenomenon. A water pump is necessary to

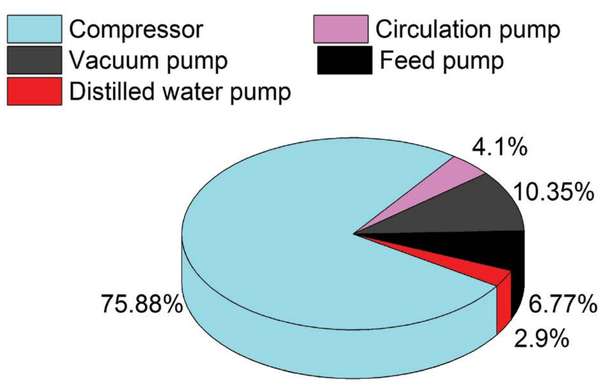

Fig. 8. Distribution of power consumption.

discharge the distilled water in tank because the distilled water cannot flow out automatically under the vacuum environment, which consumes power of 2.9% to keep the constant water level in the distilled water tank. The discharge water pump is unnecessary because the pressure of concentrated water is increased by circulation pump before it flows into evaporator, and part of concentrated water is discharged from bypass. Apparently, steam compressor is the high-energy consumption device in this system, and optimization design and regulation are very important.

The total dissolved solids (TDS) of feed water, discharge water, and distilled water are shown in Fig. 9, which expresses source taken from 10 water samples on different days. The value of discharge water reflects the concentration degree for the wastewater, and it is 40,880–78,650 mg L^{-1} for the tested samples. The TDS of distilled water directly influences not only the water quality but also the efficiency of separator. Usually, the complete separation is difficult for the separator, which means some salts are inevitably carried into the compressor

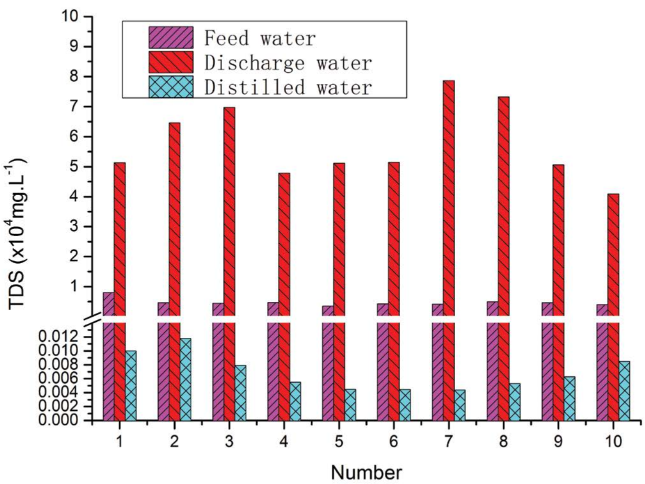

Fig. 9. TDS of feed, discharge, and distilled water.

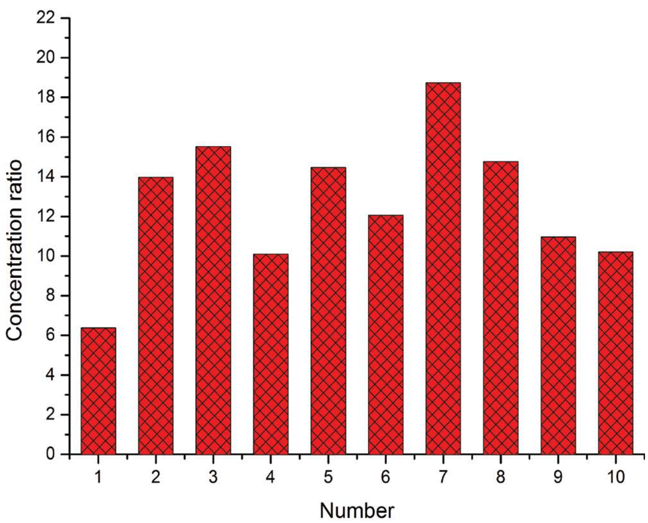

Fig. 10. Concentration ratio of water.

Table 2
Typical water quality

Item	TDS	Calcium hardness	Chemical oxygen demand	Turbidity	NH_3–N
	mg L^{-1}	mg L^{-1}	mg L^{-1}	NTU	mg L^{-1}
Feed water	6,568	22.8	455	3.5	94.6
Discharge water	122,648	35.4	/	36.5	131.4
Distilled water	111	0.8	380	0.2	70.6

by steam and finally remain in the distilled water. The tested values change within 44.6–118 mg L^{-1}, which show excellent quality of recycled water and favorable treatment.

The concentration ratio of discharge water to feed water represents the recovery degree of wastewater (Fig. 10). For a certain system, the larger concentration ratio is obtained if more salts in the feed water although the concentration of discharge water is not large enough. Limited by the pretreatment system, the maximum tested value is 18.7, which means 94.7% of feed water is recycled.

The typical water quality index for a sample is shown in Table 2. The TDS, calcium hardness, chemical oxygen demand (CODcr), turbidity, and NH_3–N of distilled water are lower than the values of feed water. All the indexes of recycled water accord with the demands of the reuse of water, which proves the combination of pretreatment and MVR system is feasible for the saline effluent of coal chemical plant.

4. Conclusions

The treatment capacity of distilled water is 0.88–1.51 t h^{-1} when the rotating speed of compressor is 20,000 rpm, and it is 0.77–1.15 t h^{-1} when the rotating speed is 19,500 rpm. The shaft power consumption of compressor increases with saturated temperature difference, and it consumes about 3.1–4 kW if saturated temperature difference increases 1°C. The compressor runs reliably, and the maximum shaft vibration amplitudes of compressor and motor are 12 and 19 μm, respectively. The average mass flow rates of feed water, discharge water, and distilled water are 1.07, 0.15, and 0.93 t h^{-1} within continuous 24 h, and the maximum fluctuations are within ±4.9%, ±6.4%, and ±5%. The compressor consumes shaft power of 24.8–28.7 kWh when 1 t distilled water is recycled. The power consumptions of compressor, vacuum pump, circulation pump, and distilled water pump are 75.9%, 10.4%, 4.1%, and 2.9%, respectively, for the whole system. The TDS of discharge water is 40,880–78,650 mg L^{-1}, and the values of distilled water are 44.6–118 mg L^{-1}, which show excellent quality for the recycled water and favorable treatment for the wastewater. The maximum concentration ratio reaches 18.7 at the tested condition, which means 94.7% of feed water is recycled.

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