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Simulation and Experimental Study of Circulatory Flash Evaporation System for High-Salt Wastewater Treatment

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Abstract: Treatment methods for high-salt wastewater mainly consist of physical methods, chemical methods and biological methods. However, there are some problems, such as slow treatment speed, high investment costs and low treatment efficiency. To address NaCl solutions, in this study, a circulatory flash system was designed based on gas–liquid equilibrium, mass conservation equation and energy conservation equation. A circulatory flash evaporation simulation and a static flash evaporation experiment were conducted on NaCl solutions under various operating conditions to investigate the effects of heating temperature, flash pressure and initial NaCl concentration on the circulatory flash evaporation system. The significance of each factor's influence on the evaporation fraction and energy consumption was examined through static flash experiments. The simulation results demonstrated that increasing the heating temperature, decreasing the flash pressure and having a higher initial NaCl concentration could enhance the treatment capacity of high-salt wastewater. The flow rate of vapor outlets increased with higher heating temperature but decreased as the flash pressure rose. The experimental results demonstrated that flash evaporation pressure was the primary factor influencing both the evaporation fraction and the energy consumption per unit mass of vapor produced. It was observed that with an increase in heating temperature, the flash pressure decreased and there was a corresponding decrease in energy consumption per unit mass of vapor produced. The optimal experimental conditions were achieved at a heating temperature of 99 °C, a flash pressure of 15 kPa, and an initial NaCl concentration of 20%.

Keywords: circulatory flash evaporation; static flash evaporation; heat and mass transfer; high-salt wastewater treatment; energy consumption analysis



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1. Introduction

“High-salt wastewater” refers to wastewater rich in organic matter, in which the mass fraction of salt substances is greater than or equal to 1% or the total dissolved solids (TDS) are greater than or equal to 3.5%. The salts are mainly Cl^- , SO_4^{2-} , Na^+ , Ca^{2+} , Mg^{2+} and other substances [1]. This kind of wastewater comes from a wide range of sources, mainly in the industrial production processes of the chemical industry, electric power generation, metallurgy, pharmaceutical production, petroleum, paper making, printing and dyeing, food processing, and seawater desalination [2]. At present, there are many conventional reduction treatment processes for high-salt wastewater, such as biochemical treatment [3], membrane permeability [4], heat treatment [5] and so on. The advantage of biochemical treatment is its low cost, but the treatment cycle is long, and the effect is poor when dealing with toxic substances that are difficult to degrade. The membrane permeation method has the advantages of simple operation, stable water production and low cost, but there are some problems, such as membrane fouling and blockage. The heat treatment method, which mainly includes multi-stage flash evaporation (MSF) [6], multi-effect evaporation

(MED) [7] and mechanical vapor recompression evaporation (MVR) [8], has the advantages of mature process and stable operation, but scale phenomena form easily in the evaporator, thereby reducing the life of the evaporator.

Flash crystallization technology refers to a heat treatment method wherein a high-pressure solution is introduced into a low-pressure environment, resulting in the rapid vaporization and saturation of the solution, followed by the precipitation of crystalline salt [9]. Compared to conventional high-salt wastewater treatment processes, this method exhibits the advantages of reduced energy consumption, enhanced evaporation efficiency and resistance to scaling. It is particularly suitable for the evaporative crystallization of highly concentrated liquids prone to scaling. According to whether the liquid has horizontal initial velocity in the process of flash evaporation, flash evaporation can be divided into static flash evaporation and circulatory flash evaporation.

Static flash evaporation is the basic form of flash evaporation, which completely shows the complete process of flash liquid transforming from the initial equilibrium state to the unstable state and finally reaching the new equilibrium state [10]. Therefore, static flash evaporation is the starting point of the study of the flash phenomenon. Gopalakrishna et al. [11] conducted a flash evaporation experiment on a pure water and 3.5% NaCl solution and proposed a formula for calculating flash evaporation amount by measuring the height change of liquid film in the superheating range of 0.5–10 °C. Saury et al. [12] conducted an experimental study on flash evaporation of pure water, and the results showed that flash evaporation tended to the limit value after some time, and evaporation increased with the increase of the initial temperature of the solution and decreased with the increase of the initial pressure of the solution. Liu et al. [13] conducted experiments on the flash evaporation process of NaCl droplets in a vacuum environment, and the results showed that with an increase of NaCl concentration, the droplet evaporation rate decreased and the droplet temperature change slowed down; with the decrease of ambient pressure, the droplet evaporation rate increased. As the initial temperature increased or the droplet size decreased, the droplet evaporation rate increased and the droplet temperature changed faster. Zhang et al. [14] conducted flash experiments with NaCl solution with a concentration of 0–15%, and the results showed that a higher concentration of NaCl could inhibit the change of gas and liquid phase in the flash process, reduced the flash rate and weakened the boiling heat transfer intensity. Yang et al. [15] studied the static flash process of NaCl solution and analyzed the variation law of flash mass under different conditions. The results showed that superheating and liquid level height were important parameters affecting evaporation quality, and evaporation mass increased with the increase of liquid level height and superheating. Zhang et al. [16] conducted experimental studies on NaCl solution under different working conditions, and the results showed that the concentration of NaCl had no significant effect on the flash rate, and the flash rate gradually decreased with the increase of superheat.

Circulatory flash evaporation is a kind of flash evaporation extracted from the background of industrial continuous production. Due to the existence of horizontal velocity in flash film, the temperature change and boiling form of flash film are different from those of static flash evaporation. In the circulatory flash evaporation study, Wang et al. [17] conducted a flash evaporation experiment with a NaCl solution with a concentration of 15% and analyzed the effects of different parameters on the non-equilibrium fraction. The results showed that the non-equilibrium fraction decreased with the increase of the flash rate; when the circulatory flash rate was the same, the non-equilibrium fraction decreased with the increase of superheat and equilibrium pressure. Zhang et al. [18] conducted flash experiments on pure water, and the results showed that when the liquid film height and superheat were constant, the non-equilibrium fraction decreased with the increase of flash pressure and circulating flow rate; when the flash pressure, circulatory flow rate and superheat were constant, the non-equilibrium fraction increased with the increase of liquid film height. Wang et al. [10] conducted an experimental study on the flash rate of NaCl solution, and the results showed that the circulatory flash rate increased with the

increase of the circulatory flow rate and the equilibrium pressure. The circulatory flash rate decreased with the increase of NaCl concentration and liquid level height; with the increase of superheat, the flash rate decreased first and then increased. Zhang et al. [19] conducted an experimental study on the non-equilibrium fraction of NaCl solution and analyzed the effects of different mass flow rate, liquid level height, flash pressure and NaCl concentration on the non-equilibrium fraction. The results showed that under the same superheated condition, the non-equilibrium fraction decreased with the increase of mass flow rate and flash pressure, and increased with the increase of liquid level height and NaCl concentration. Wang et al. [20] analyzed the energy and exergy of NaCl solution circulatory flash process, and the result showed that as the liquid level height and NaCl concentration decreased, the energy utilization rate increased, and increased equilibrium pressure could improve the energy utilization rate.

At present, flash technology had been widely used in desalination [21], sewage treatment [22], drying technology and other industrial applications. In previous studies, scholars have analyzed the effects of circulatory flow rate, flash pressure, initial solution concentration and solution superheating on evaporation rate and imbalance fraction during circulatory flash evaporation. This study takes NaCl solution as the research object, conducts research on the evaporation characteristics of high-salt wastewater, uses range and variance analysis methods to explore the significance of different factors on the flash evaporation process, studies the changes in energy consumption and evaporation fraction under different factors and obtains the optimal operating conditions. Research is conducted on the steady-state performance of the circulatory flash evaporation system to establish a steady-state mathematical model of the circulatory flash evaporation system and verify the theoretical model of the system based on experimental results. Changes in flow rate and concentration at various operating points within the system under different parameters are also studied, providing a basis for parameter control of the circulatory flash evaporation system. The study of these parameters plays an important role in further improving the efficiency of circulatory flash evaporation, reducing energy consumption, and achieving industrial application.

2. Circulatory Flash Evaporation System

The circulatory flash evaporation system is shown in Figure 1. The system is built based on the equations of conservation of energy and conservation of mass, and is a heat flow recirculation loop. The circulatory flash evaporation system mainly consists of a heater, a flash crystallizer, a vacuum pump, a solid–liquid separator, a flow control valve and two solution pumps. Initially, the high-salt wastewater flows into the heater inlet, is heated to the target temperature by the heater and then enters the flash crystallizer. After being concentrated and evaporated, the vapor produced by flash evaporation is discharged from the outlet of the flash crystallizer, while the concentrated liquid enters the solid–liquid separator. After being separated by a solid–liquid separator, the crystalline salt precipitated through flash evaporation is discharged from the outlet of the solid–liquid separator, while the remaining brine enters the heater.

During the simulation, the circulatory flash evaporation process was modeled as a steady-state phenomenon using Engineering Equation Solver (V10.561) software for computational analysis, with negligible consideration given to heat dissipation within the system. According to the principle of gas–liquid equilibrium, the liquid level in both the heater and flash crystallizer was maintained at a constant height. Therefore, after undergoing multiple cycles, the high-salt wastewater introduced into the flash crystallizer eventually transforms into a highly concentrated solution.

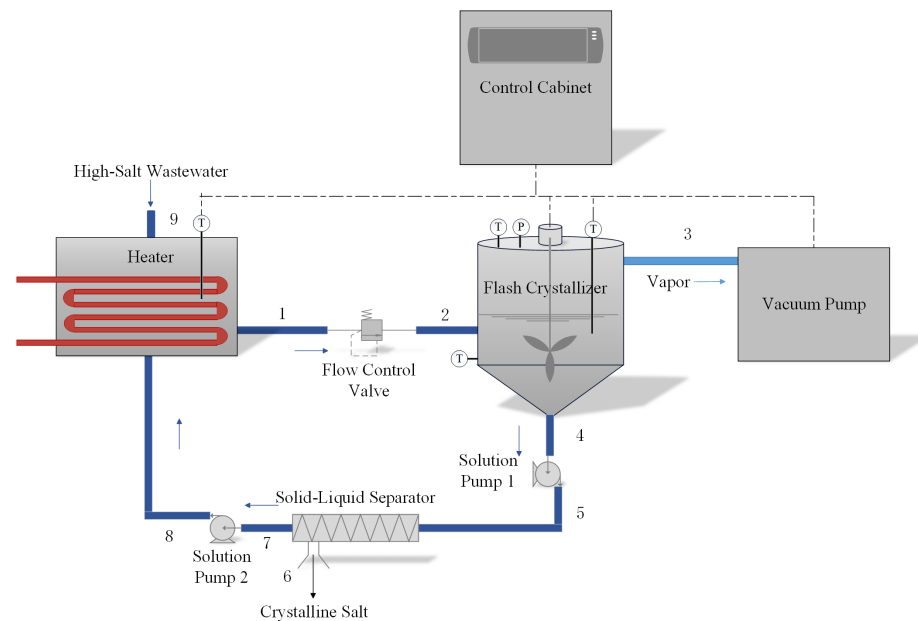


Figure 1. Schematic diagram of circulatory flash evaporation system.

3. Experimental and Theory

3.1. Experimental

3.1.1. Experimental Method

The experimental system mainly consists of a heater, a flash crystallizer, a vacuum pump, a control cabinet and a flow control valve. The flash evaporator is a key component of the circulating flash evaporation system, which is a barrel with an inner diameter of 0.6 m and a height of 1.2 m. To prevent scaling on the walls of the crystallizer, the flash evaporation crystallizer is equipped with blades inside and controlled by a top motor. At the top of the flash crystallizer, there is a vacuum gauge with a maximum range of 0.1 MPa and a temperature gauge with a maximum range of 100 °C, and a T-type thermocouple is installed inside. The heater is a stainless steel barrel with a diameter of 0.8 m and a heating coil at the bottom, with a T-type thermocouple installed inside. The vacuum pump creates a low-pressure environment in the flash crystallizer. The control cabinet is used for displaying the thermocouple temperature and controlling the equipment's start and stop.

The high-salt wastewater used in the experiment is a self-prepared NaCl solution. For the experiment, the heater was switched on and the high-salt wastewater was heated to the target temperature. Then the vacuum pump was opened, and the flash crystallizer pressure was adjusted to the target pressure through the vacuum pump. During the final stage, the flow control valve was opened to adjust the flow at the inlet of the flash crystallizer. During the experiment, the vapor generated by flash evaporation was discharged from the top outlet of the flash crystallizer. After the flash was completed, the vacuum pump was closed and the bottom outlet of the flash crystallizer was opened. After the pressure relief of the flash crystallizer was completed, the concentrated liquid was discharged from the bottom outlet of the flash crystallizer.

During the experiment, the evaporation fraction and the energy consumption per unit mass of vapor produced were used as evaluation indexes for the static flash evaporation experiments. The evaporation fraction is defined as the ratio of the mass of evaporated vapor to the mass of the initial solution. The calculation formula is Equation (1),

$$r = \frac{m_{in} - m_{out}}{m_{in}} \quad (1)$$

where m_{out} is the mass of solution at the exit of the flash crystallizer, and m_{in} is the inlet solution mass of the flash crystallizer.

The energy consumption of the static flash evaporation experiment mainly consisted of the heater energy consumption and the vacuum pump energy consumption. The calculation formula is Equation (2),

$$Q_{all} = Q_h + Q_y \quad (2)$$

where Q_h is the heater energy consumption, Q_y is the vacuum pump energy consumption, and Q_{all} is the total energy consumption. Heater energy consumption refers to the energy consumption required by heating the solution from room temperature to the target temperature, which is calculated based on heater power and the heating time. Vacuum pump energy consumption indicates the energy consumption required by the vacuum pump to maintain the pressure inside the flash crystallizer, which is calculated based on vacuum pump power and flash duration. Total energy consumption refers to the sum of heater energy consumption and vacuum pump energy consumption, which is the energy consumption required for each complete operation of the experimental system.

The energy consumption per unit mass of vapor produced Q_x is defined as the energy consumption required to generate 1 kg of vapor. When treating the same weight of high-salt wastewater, the larger the energy consumption per unit mass of vapor produced, the larger the energy consumption consumed by the system. The calculation formula is Equation (3):

$$Q_x = \frac{Q_{all}}{m_{in} - m_{out}} \quad (3)$$

3.1.2. Experimental Design

Heating temperature, flash pressure and initial NaCl concentration were important factors affecting evaporation fraction and energy consumption per unit mass of vapor produced. Orthogonal experiments were used to study the degree of influence of different factors on the evaporation fraction and energy consumption per unit mass of vapor produced and obtain the optimum operating conditions. Control variable experiments were used to further investigate the effects of heating temperature and flash pressure on evaporation fraction and energy consumption per unit mass of vapor produced under optimum operating conditions.

Orthogonal experiments were selective based on a designed orthogonal table. The range analysis method was used to process the data to obtain the importance of the factors influencing the results and the best working conditions. When the range of the factor was larger, the impact of the factor on the result was greater, and when the range of the factor was smaller, the impact of the factor on the result was smaller. Analysis of variance could be used to verify the range analysis results and obtain the significance of each factor's influence on the experimental results. The significance of the influence of the factor on the result could be judged according to the significance of the factor; when the significance of the factor was smaller, the impact of the factor on the result was greater, and when the significance of the factor was larger, the impact of the factor on the result was smaller. The orthogonal method was used to set up sixteen sets of orthogonal experimental conditions with three factors and four levels; the three-factor level table is shown in Table 1. The heating temperatures were 87 °C, 91 °C, 95 °C and 99 °C; the flash evaporation pressures were 15 kPa, 20 kPa, 25 kPa, and 30 kPa; the initial NaCl concentrations were 10%, 15%, 20%, and 25%; and the orthogonal experiments are shown in Table 2.

Table 1. Factor level table.

Number	Heating Temperature (°C)	Flash Pressure (kPa)	Initial NaCl Concentration (%)
1	87	15	10
2	91	20	15
3	95	25	20
4	99	30	25

Table 2. Orthogonal experiment table.

Number	Heating Temperature (°C)	Flash Pressure (kPa)	Initial NaCl Concentration (%)
1	99	20	15
2	95	25	10
3	87	15	10
4	91	25	20
5	99	30	10
6	95	30	25
7	95	20	20
8	91	20	10
9	91	30	15
10	95	15	15
11	99	25	25
12	99	15	20
13	91	15	25
14	87	25	15
15	87	30	20
16	87	20	25

The control variable experiments were designed according to the best operating condition points of orthogonal experiments; the heating temperatures were 87 °C, 91 °C, 95 °C and 99 °C; and the flash evaporation pressures were 15 kPa, 20 kPa, 25 kPa, and 30 kPa. The initial NaCl concentration was not an important factor affecting the evaporation fraction and the energy consumption per unit mass of vapor produced. Therefore, the initial NaCl concentration was 20% of the best operating concentration of the orthogonal experiments, and the control variable experiments are shown in Table 3.

Table 3. Control variable experiment table.

Number	Heating Temperature (°C)	Flash Pressure (kPa)	Initial NaCl Concentration (%)
1	99	15	20
2	95	15	20
3	91	15	20
4	87	15	20
5	99	20	20
6	99	25	20
7	99	30	20

3.2. Theoretical Model

3.2.1. Mathematical Model

Set high-salt wastewater was used as the NaCl solution during the model-building process. Based on the principle of the gas–liquid phase equilibrium, the formula for calculating the saturation vapor pressure of a NaCl solution is Equation (4),

$$p = \gamma \chi p_s \quad (4)$$

where γ is the activity coefficient, and the value of the activity coefficient in Aspen is 1, χ is the mole fraction of water, and p_s is the saturated vapor pressure of water, which can be calculated using Antoine's formula,

$$\log p_s = A - \frac{B}{t + C} \quad (5)$$

where A , B and C are the physical property constants: $A = 7.96681$, $B = 1668.21$, and $C = 228$.

During the heating process, the liquid heating temperature range is 87–99 °C, and the average constant pressure specific heat capacity of water can be taken as 4.1868 kJ/(kg K). The enthalpy value of water is expressed by Equation (6),

$$h_{\text{water}} = \int_{t_0}^{t_1} c_{p,\text{water}} dt \quad (6)$$

The average specific heat capacity of NaCl is represented by Equation (7),

$$c_{p,\text{NaCl}} = 0.045 + 0.0005t \quad (7)$$

The enthalpy value of NaCl is expressed by Equation (8),

$$h_{\text{NaCl}} = \int_{t_0}^{t_1} c_{p,\text{NaCl}} dt \quad (8)$$

The heat of NaCl dissolution is represented by Equation (9),

$$h_r = \frac{1.164 \times 4.18w_i}{0.05844} \quad (9)$$

Therefore, the enthalpy value of high salinity wastewater is represented by Equation (10),

$$h_{\text{sw}} = wh_{\text{NaCl}} + (1 - w)h_{\text{water}} + h_r \quad (10)$$

where t_0 is the initial temperature of the liquid, °C; t_1 is the liquid heating temperature, °C; h_{water} is the enthalpy value of water, kJ/kg; $c_{p,\text{water}}$ is the specific heat capacity of water, kJ/(kg·K); $c_{p,\text{NaCl}}$ is the specific heat capacity of NaCl, kJ/(kg·K); h_{NaCl} is the enthalpy value of NaCl, kJ/kg; w_i is the concentration of NaCl, %; h_r is the heat of NaCl dissolution, kJ/kg; and h_{sw} is the enthalpy value of high salinity wastewater, kJ/kg.

During the flashing process, when the liquid temperature reaches the saturation temperature corresponding to the flashing pressure, it is held that the saturated liquid has not undergone boiling. When the temperature of the liquid is higher than the saturation temperature corresponding to the flash pressure, the liquid boils and produces superheated vapor. The excess heat q_{sup} is represented by Equation (11),

$$q_{\text{sup}} = \int_{t_s}^{t_1} c_{p,\text{water}} dt \quad (11)$$

The average specific heat capacity of water vapor is represented by Equation (12),

$$c_{p,\text{water}} = 1.833 + 0.000311t \quad (12)$$

where t_s is the saturation temperature corresponding to the flash pressure, °C.

Construction of a circulatory flash evaporation system is performed by coupling the equations of conservation of mass and conservation of energy. Each point corresponds to the Figure 1 state point.

The heater mass conservation model is Equation (13),

$$q_{m,9} + q_{m,8} = q_{m,1} \quad (13)$$

The heater energy conservation model is Equations (14)–(17),

$$Q_c + q_{m,9}h_9 + q_{m,8}h_8 = q_{m,1}h_1 \quad (14)$$

$$h_9 = w_9h_{\text{NaCl}} + (1 - w_9)h_{\text{water}} + h_{r,9} \quad (15)$$

$$h_8 = w_8h_{\text{NaCl}} + (1 - w_8)h_{\text{water}} + h_{r,8} \quad (16)$$

$$h_1 = w_1 h_{NaCl} + (1 - w_1) h_{water} + h_{r,1} \quad (17)$$

The flash crystallizer mass conservation model is Equation (18),

$$q_{m,2} = q_{m,3} + q_{m,4} \quad (18)$$

The flash crystallizer energy conservation model is Equations (19) and (20),

$$q_{m,2} h_2 = q_{m,3} h_3 + q_{m,4} h_4 \quad (19)$$

$$h_4 = w_4 h_{NaCl} + (1 - w_4) h_{water} + h_{r,4} \quad (20)$$

The solid–liquid separator mass conservation model is Equation (21),

$$q_{m,5} = q_{m,6} + q_{m,7} \quad (21)$$

The solid–liquid separator energy conservation model is Equation (22),

$$q_{m,5} h_5 = q_{m,6} h_6 + q_{m,7} h_7 \quad (22)$$

The mass conservation model for circulatory flash evaporation system is Equation (23),

$$q_{m,9} = q_{m,3} + q_{m,6} \quad (23)$$

The energy conservation model for circulatory flash evaporation system is Equation (24),

$$Q_c + q_{m,9} h_9 = q_{m,3} h_3 + q_{m,6} h_6 \quad (24)$$

where $q_{m,i}$ is the mass flow rate at each state point. Q_c is the heater heat, h_i is the enthalpy at each state point, h_{NaCl} is the enthalpy of NaCl, h_{Water} is the enthalpy of water, $h_{r,i}$ is the heat of dissolution of NaCl at each state point, and w_i is the mass fraction of NaCl at each state point.

Based on the theoretical model of the circulatory flash evaporation system mentioned above, the engineering equation solver program Engineering Equation Solver (EES) was used to simulate and calculate the circulatory flash evaporation system. By setting the flash crystallizer inlet flow rate to 1 kg/s, heating temperature to 87 °C, flash pressure to 20 kPa, and initial NaCl concentration to 10%, simulations were conducted for each state point as presented in Table 4. The obtained results demonstrate compliance with the principles of energy and mass conservation through calculations of temperature, pressure, mass flow rate, enthalpy, and NaCl concentration at each state point.

Table 4. Parameters for each state point of circulatory flash evaporation system.

State	T (°C)	p (kPa)	q_m (kg·s ^{−1})	h (kJ·kg ^{−1})	w (%)
1	87	100	1	309.7	26.59
2	87	20	1	309.7	26.59
3	62.44	20	0.035	2614	0
4	62.44	20	0.956	227.5	27.55
5	62.44	100	0.956	227.5	27.55
6	62.44	100	0.004	212.9	100
7	62.44	100	0.961	227.5	27.26
8	62.44	100	0.961	227.5	27.26
9	25	100	0.039	104.9	10

3.2.2. Algorithmic Process

Figure 2 shows the algorithmic process of the circulatory flash evaporation system. The first step assumed that the concentration of high-salt wastewater in the heater was X_1 , and then calculated the enthalpy h_1 of high-salt wastewater at the outlet of the heater

and the mass flow rate $q_{m,1}$. The second step assumed that the flash crystallizer produced a vapor flow rate $q_{m,3}$, and then calculated the enthalpy h_3 of the vapor at the outlet of the flash crystallizer, the enthalpy h_4 of the high-salt wastewater concentrate and the mass flow rate $q_{m,4}$. The third step was to judge whether the flash crystallizer satisfied energy conservation according to the energy conservation equation: if it satisfied the energy conservation equation, the process continued; if it did not satisfy the energy conservation equation, the produce vapor flow $q_{m,3}$ was reset. In the fourth step, the enthalpy h_6 of crystallized salt at the outlet of the solid–liquid separator and the mass flow rate $q_{m,6}$, the enthalpy h_7 of refluxed salt solution and the mass flow rate $q_{m,7}$ were calculated according to the equations of conservation of mass and energy. The fifth step calculated the concentration X_2 of high-salt wastewater in the heater according to the mass conservation equation. The sixth step was to judge whether the calculated value of the concentration of high-salt wastewater in the heater and the set value were equal: if they were equal, then the end of the calculation result was retained; if they were not equal, then the concentration X_1 of high-salt wastewater in the heater was reset.

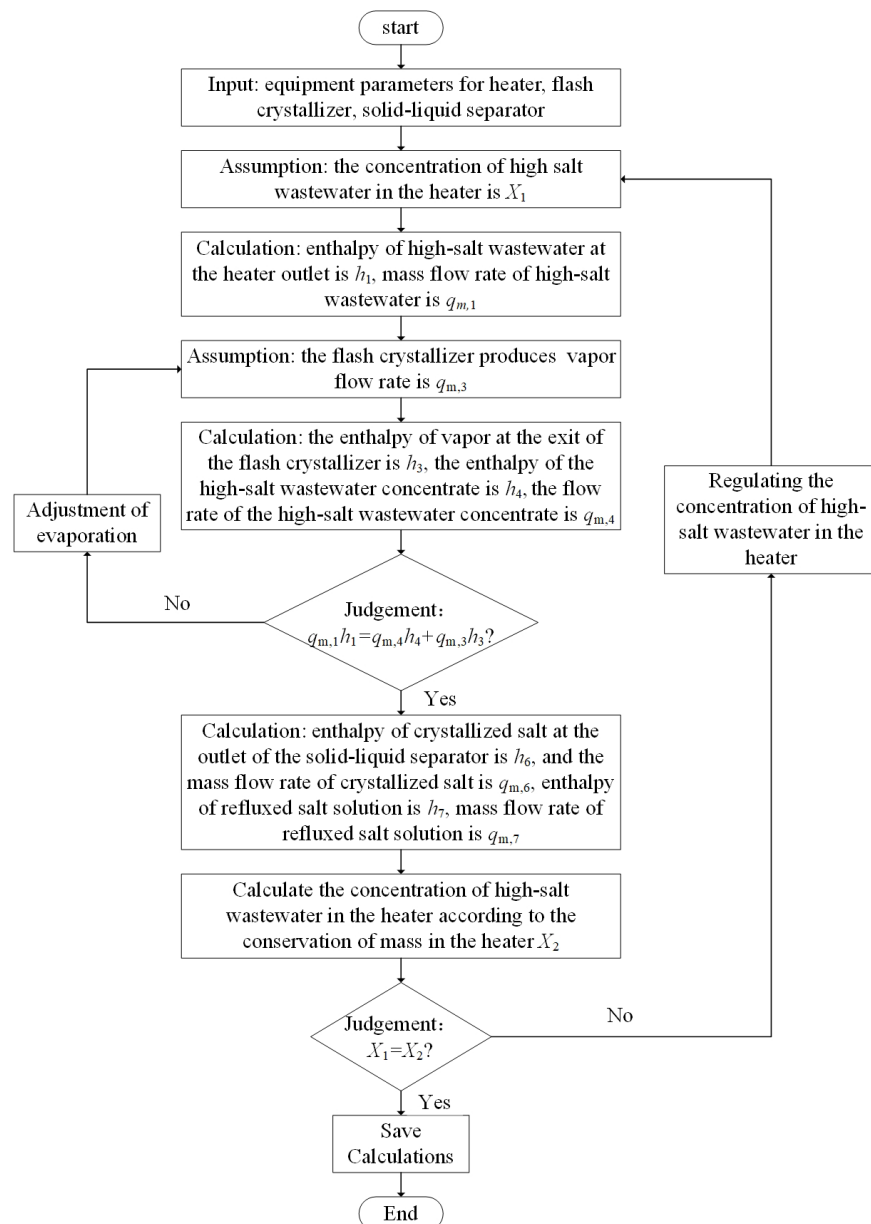


Figure 2. Algorithmic process diagram for circulatory flash evaporation system.

3.2.3. Model Validation

As shown in Figure 3, the experimental results were verified with simulation results for 16 sets of orthogonal experiments. Figure 3a shows the variation in the evaporation fraction, and Figure 3b shows the variation in the flash equilibrium temperature, where flash equilibrium temperature refers to the temperature of the liquid at the end of flash evaporation in the flash crystallizer.

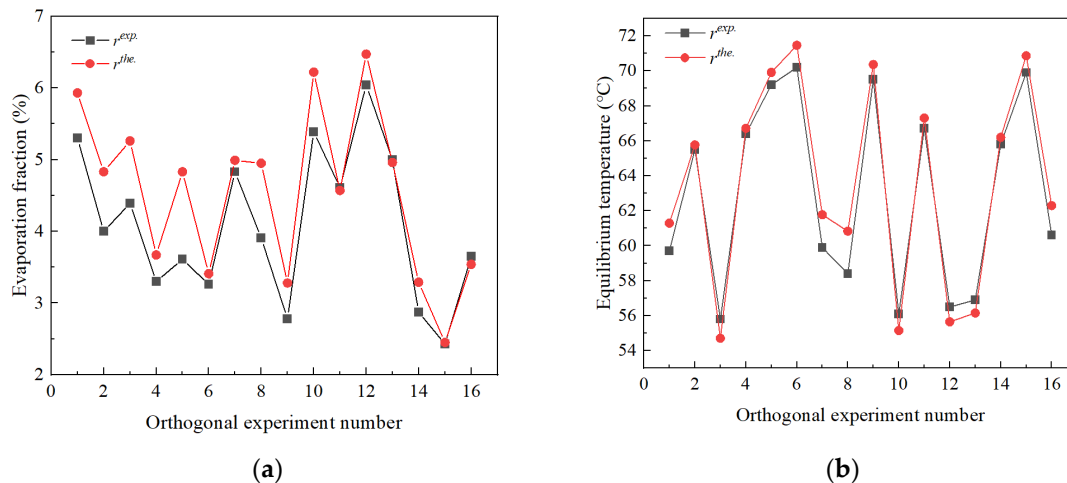


Figure 3. Validation of orthogonal experimental results with simulation results. (a) Comparison of evaporation fraction, (b) Comparison of flash equilibrium temperature.

As shown in the figure, the experimental values of the evaporation fraction and the simulated values of flash equilibrium temperature have the same trend. In the change of evaporation fraction, the maximum difference between the experimental and simulated values of group 5 is 25.3%, and the minimum difference between the experimental and simulated values of group 13 is 0.8%. In the change of equilibrium temperature, the maximum difference between the experimental and simulated values of group 8 is 4.0%, and the minimum difference between the experimental and simulated values of group 4 is 0.5%. In summary, the simulation results are highly consistent with the experimental results, and the theoretical model of the circulatory flash evaporation system is reliable.

4. Results

4.1. Theoretical Results and Analyses

This section mainly adopts the simulation method. The heating temperature is set at 91 °C, the flash pressure is 20 kPa, and the initial NaCl concentration is 10%. The heating temperature refers to the temperature of the NaCl solution at the outlet of the heater, the flash pressure refers to the absolute pressure inside the flash crystallizer, and the initial NaCl concentration refers to the concentration of high-salt wastewater at the entrance of the heater. By changing the control variable, the mass flow rate and NaCl concentration at each state point of the circulatory flash system are calculated.

4.1.1. Effect of Heating Temperature on Circulatory Flash Evaporation System

Figure 4a shows the flash pressure of 20 kPa, the initial NaCl concentration of 10%, the heating temperature of 87–99 °C within the range of change, the change of the vapor outlet flow rate $q_{m,3}$, the crystalline salt outlet flow rate $q_{m,6}$ and the high-salt wastewater inlet flow rate $q_{m,9}$. The results show that the vapor outlet flow rate increases with increasing heating temperature, the amount of high-salt wastewater treated increases, and the crystalline salt outlet flow rate increases. The explanation is provided as follows. The flash pressure is considered to be the factor that changes the gas–liquid phase equilibrium temperature in the circulatory flash evaporation system; the heating temperature and initial NaCl have less

influence on the gas–liquid phase equilibrium temperature. Consequently, with an increase in the heating temperature, the temperature differential between the heating temperature and the equilibrium temperature of the gas–liquid phase amplifies, thereby enhancing heat transfer within this phase. This increased heat is then converted into the latent heat of vaporization, resulting in a subsequent rise in vapor outlet flow rate. The inlet flow rate of the flash crystallizer is a constant value; as the outlet flow rate of vapor increases, there is an increase in NaCl concentration at the outlet of the flash crystallizer. Consequently, the inlet flow rate of the solid–liquid separator decreases due to the presence of NaCl crystalline salt and saturated NaCl solution as major components in the solution at the outlet of the flash crystallizer, resulting in an increase in the crystalline salt outlet flow rate. Given the adherence of the system to the conservation of mass model, an increase in both vapor outlet flow rate and crystalline salt outlet flow rate leads to a corresponding increase in high-salt wastewater inlet flow rate, thereby resulting in an augmented volume for high-salt wastewater treatment.

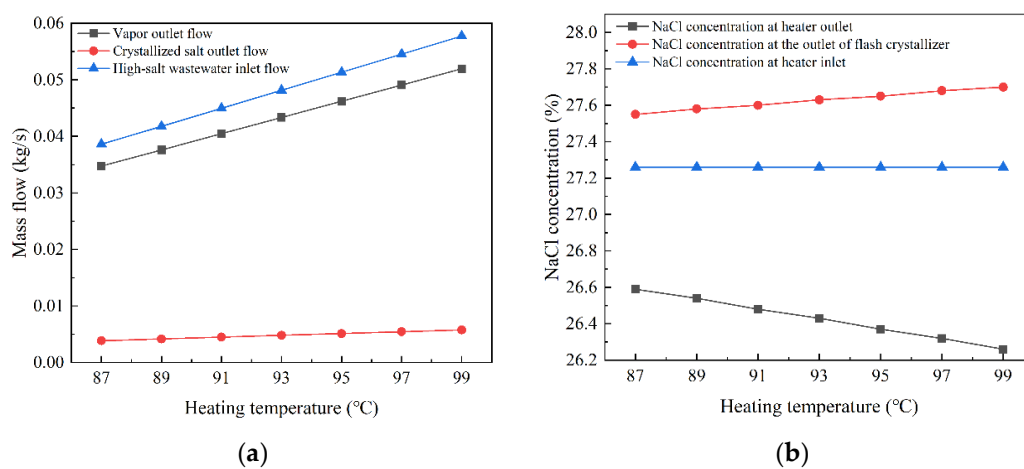


Figure 4. Effect of heating temperature on circulatory flash evaporation system. (a) Mass flow change, (b) NaCl concentration change.

Figure 4b shows the change of NaCl concentration at heater outlet w_1 , NaCl concentration at the outlet of the flash crystallizer w_4 and NaCl concentration at heater inlet w_8 . The results show that, with the increase of heating temperature, the heater inlet NaCl concentration is unchanged, the heater outlet NaCl concentration decreases, and the flash crystallizer outlet NaCl concentration increases. The explanation is provided as follows. The gas–liquid phase equilibrium temperature is the same at the same flash pressure, the solubility of NaCl solution in the flash crystallizer is the same, and as the heating temperature rises, the vapor outlet flow rate increases, and the concentration of NaCl at the flash crystallizer outlet increases. The outlet solution of the flash crystallizer primarily consists of NaCl crystalline salt and a saturated NaCl solution. Consequently, the concentrated reflux from the solid–liquid separator is also a saturated NaCl solution. Additionally, the solubility of the NaCl solution remains constant at different heating temperatures, thus, maintaining a consistent inlet concentration of NaCl in the heater. The outlet NaCl concentration of the heater decreases as the flow rate of high-salt wastewater inlet increases, due to dilution caused by a lower NaCl concentration in the high-salt wastewater compared to that at the heater inlet.

4.1.2. Effect of Flash Pressure on Circulatory Flash Evaporation System

Figure 5a shows the heating temperature of 91 °C, the initial NaCl concentration of 10%, the flash evaporation pressure 15 kPa–30 kPa within the range of change, the change of the vapor outlet flow rate $q_{m,3}$, crystalline salt outlet flow rate $q_{m,6}$ and high-salt wastewater inlet flow rate $q_{m,9}$. The results show that as the flash pressure decreases, the vapor outlet

flow rate increases, the amount of high-salt wastewater treated increases, and the crystalline salt outlet flow rate increases. The explanation is provided as follows. The gas–liquid phase equilibrium temperature decreases with decreasing flash pressure, leading to an increased temperature difference between the heating temperature and the gas–liquid phase equilibrium temperature. Consequently, there is an enhancement in gas–liquid phase heat transfer, resulting in an augmented vapor outlet flow rate. The flash crystallizer inlet flow rate is certain; when the steam outlet flow rate increases, the solid–liquid separator inlet flow rate decreases, and the gas–liquid phase equilibrium temperature decreases, leading to a decrease in the solubility of the NaCl solution, which results in an increase in the content of NaCl crystalline salt precipitated from the solution and an increase in the crystalline salt outlet flow rate. Given the adherence of the system to the conservation of mass model, an increase in both vapor outlet flow rate and crystalline salt outlet flow rate leads to a corresponding increase in high-salt wastewater inlet flow rate, thereby resulting in an augmented volume for high-salt wastewater treatment.

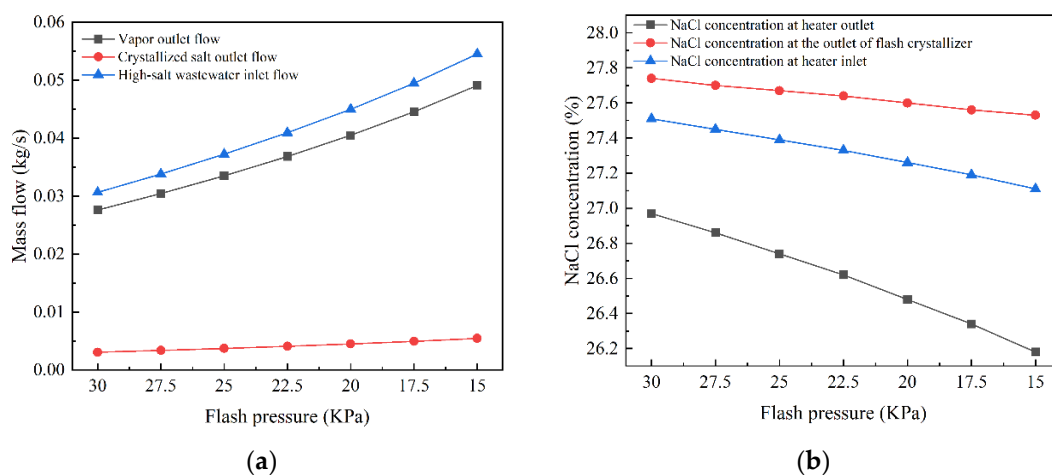


Figure 5. Effect of flash pressure on circulatory flash evaporation system. (a) Mass flow change, (b) NaCl concentration change.

Figure 5b shows the change of NaCl concentration at heater outlet w_1 , NaCl concentration at the outlet of the flash crystallizer w_4 and NaCl concentration at heater inlet w_8 . The results show that, with the reduction of flash pressure, the heater inlet and outlet NaCl concentration is reduced, and the NaCl concentration of the flash crystallizer outlet is reduced. The explanation is provided as follows. As the flash crystallizer outlet solution mainly consists of NaCl crystalline salt and saturated NaCl solution, when the gas–liquid phase equilibrium temperature is lowered, the solubility of the NaCl solution at the flash crystallizer outlet is lowered, so that the concentration of saturated NaCl solution at the flash crystallizer outlet is lowered, and after the separation of the NaCl crystalline salt by the solid–liquid separator, the remaining concentrate is saturated NaCl solution, so that the concentration of NaCl at the inlet of the heater is lowered. The outlet NaCl concentration of the heater decreases as the flow rate of high-salt wastewater inlet increases, due to dilution caused by a lower NaCl concentration in the high-salt wastewater compared to that at the heater inlet. Due to the decrease in NaCl concentration at the heater outlet, there is a subsequent reduction in the NaCl solution entering the flash crystallizer, resulting in a decrease in NaCl concentration at the outlet of the flash crystallizer.

4.1.3. Effect of Initial NaCl Concentration on Circulatory Flash Evaporation System

Figure 6a shows the heating temperature of 91 °C, the flash pressure of 20 kPa, the initial NaCl concentration of 10–25% within the range of change, the change of the vapor outlet flow rate $q_{m,3}$, crystalline salt outlet flow rate $q_{m,6}$ and high-salt wastewater inlet flow rate $q_{m,9}$. The results showed that as the initial NaCl concentration increased, the

vapor outlet flow rate slightly decreased, the high-salt wastewater inlet flow rate increased, and the crystallization salt outlet flow rate increased. The explanation is provided as follows. The flash pressure and heating temperature being constant, the temperature difference between the heating temperature and the gas–liquid phase equilibrium temperature remains unchanged, resulting in a consistent gas–liquid phase heat transfer quantity. However, the vapor outlet flow rate slightly decreases, so an increase in NaCl concentration inhibits the evaporation of high-salt wastewater, but this effect is relatively small. Given the identical gas–liquid phase equilibrium temperatures, the solubility of NaCl solutions remains constant. However, an increase in the initial NaCl concentration leads to a higher precipitation of crystalline salt, resulting in an augmented outlet flow rate of crystalline salt. The conservation of mass model is upheld by the system; thus, when there is minimal change in vapor outlet flow rate but an increase in crystalline salt outlet flow rate, it leads to a corresponding increase in high-salt wastewater inlet flow rate and subsequently enhances the volume of high-salt wastewater treatment.

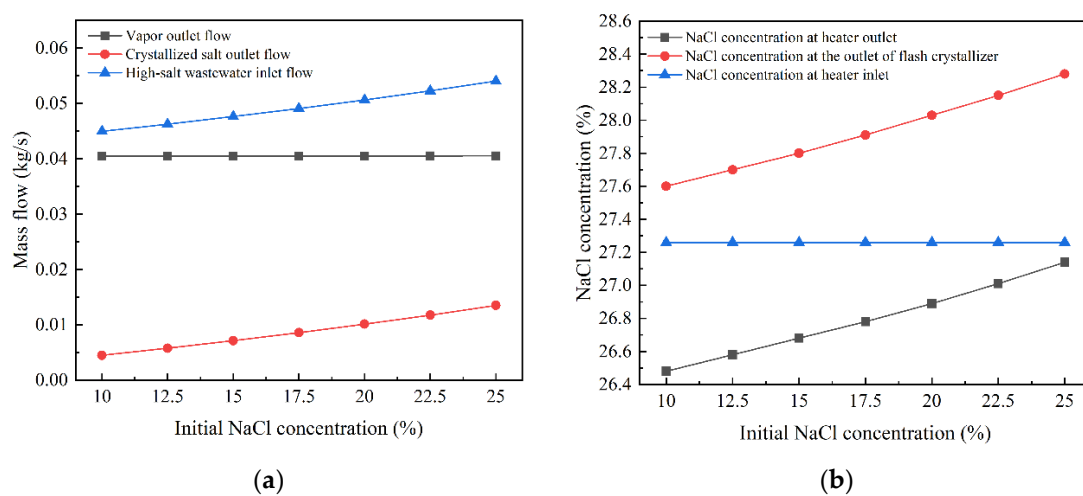


Figure 6. Effect of initial NaCl concentration on circulatory flash evaporation system. (a) Mass flow change, (b) NaCl concentration change.

Figure 6b shows the change of NaCl concentration at heater outlet w_1 , NaCl concentration at the outlet of the flash crystallizer w_4 and NaCl concentration at heater inlet w_8 . The results show that, when the initial NaCl concentration increases, the heater inlet NaCl concentration is basically unchanged, the heater outlet NaCl concentration increases, and the NaCl concentration of the flash crystallizer outlet increases. The explanation is provided as follows. The increase in initial NaCl concentration leads to a corresponding increase in the inlet NaCl concentration of the flash crystallizer, while the vapor outlet flow rate remains relatively constant, resulting in an elevation of the outlet NaCl concentration of the flash crystallizer. Since the solubility of NaCl solution remains constant, the concentration of saturated NaCl solution at the outlet of the flash crystallizer remains unchanged. After separation through a solid–liquid separator, the remaining concentrate is still a saturated NaCl solution, ensuring that there is no change in the concentration of NaCl at the inlet of the heater. The concentration of NaCl at the outlet of the heater increases as a result of an elevated NaCl concentration and flow rate at the inlet of high-salt wastewater, leading to an increase in the NaCl solution within the heater.

In summary, the treatment capacity of high-salt wastewater can be enhanced by increasing the heating temperature, reducing the flash pressure and elevating the initial NaCl concentration. The vapor outlet flow rate is primarily influenced by the heating temperature and flash pressure. As the heating temperature increases and flash pressure decreases, there is an increase in vapor outlet flow rate. The outlet flow of crystalline salt is

mainly affected by changes in initial NaCl concentration. With an increase in initial NaCl concentration, there is a corresponding rise in crystalline salt outlet flow.

4.2. Experimental Results and Discussion

4.2.1. Static Flash Evaporation Orthogonal Experiment

(1) Evaporation fraction analysis

The evaporation amount and the evaporation fraction of the same mass of solution, as determined through orthogonal experiments, are presented in Table 5. Among these, the highest evaporation recorded is 1.39 kg with an associated fraction of 6.04%, while the lowest evaporation observed is 0.56 kg with a corresponding fraction of 2.43%. Range analysis and variance analysis are conducted for evaporation fraction, as shown in Tables 6 and 7.

Table 5. Evaporation data sheet.

Number	Evaporation Amount (kg)	Evaporation Fraction (%)
1	1.22	5.3
2	0.92	4
3	1.01	4.39
4	0.76	3.3
5	0.83	3.61
6	0.75	3.26
7	1.11	4.83
8	0.9	3.91
9	0.64	2.78
10	1.24	5.39
11	1.06	4.61
12	1.39	6.04
13	1.15	5
14	0.66	2.87
15	0.56	2.43
16	0.84	3.65

Table 6. Evaporation fraction range analysis table.

	Heating Temperature (°C)	Flash Pressure (kPa)	Initial NaCl Concentration (%)
K_{i1}	19.56	17.69	16.34
K_{i2}	17.48	14.78	15.91
K_{i3}	13.34	20.82	16.6
K_{i4}	14.99	12.08	16.52
k_{i1}	4.89	4.422	4.085
k_{i2}	4.37	3.695	3.978
k_{i3}	3.335	5.205	4.15
k_{i4}	3.748	3.02	4.13
R_i	1.555	2.185	0.172

The range analysis of evaporation fractions is presented in Table 6; the range of each factor is 1.555, 2.185 and 0.172, respectively, indicating that flash pressure exhibits the most significant influence on evaporation fraction, followed by heating temperature, while the initial NaCl concentration has a relatively minor effect. The analysis of variance in Table 7 reveals that the significance levels for each factor are 0.156, 0.005, and 0.997, respectively. Notably, the initial NaCl concentration exhibits the highest significance level while flash pressure demonstrates the lowest significance level. Consequently, based on the variance analysis table, it can be concluded that flash pressure is the primary factor influencing evaporation fraction, whereas the initial NaCl concentration has a minimal effect. The results of variance analysis align with those obtained from range analysis, indicating that

the optimal parameters for evaporation fraction are heating temperature of 99 °C, flash pressure of 15 kPa, and initial NaCl concentration of 20%.

In summary, the findings from the range analysis and variance analysis indicate that both heating temperature and flash pressure exert an influence on the evaporation fraction. However, it is observed that the impact of flash pressure on the evaporation fraction is more significant, while the initial NaCl concentration has a negligible effect.

(2) Energy Consumption Analysis

The energy consumption data obtained from the orthogonal experiment are presented in Table 8. Energy consumption primarily encompasses heater energy consumption Q_h , vacuum pump energy consumption Q_v , total energy consumption Q_{all} and unit mass vapor energy consumption Q_x . When the heating temperature is 99 °C, the flash pressure is 15 kPa, the initial NaCl concentration is 20%, the minimum energy consumption per unit mass of vapor is 7162.66 kJ, and the ratio of this energy consumption to the latent heat of the vapor is 3.2. When the heating temperature is 87 °C, the flash pressure is 30 kPa, the initial NaCl concentration is 20%, the highest energy consumption per unit mass of vapor is 13,323.75 kJ, and the ratio of this energy consumption to the latent heat of the vapor is 5.9. As an analysis of the reasons, although an increase in heating temperature will increase thermal energy consumption and increase the temperature difference between heating temperature and flash equilibrium temperature, reducing flash pressure can increase flash rate, thereby shortening flash time and reducing energy consumption of the vacuum pump.

Table 7. Evaporation fraction variance analysis table.

	Sum of Squares of Deviation	Degree of Freedom	Mean Square	F	Significance
Heating temperature	5.623	3	1.874	2.081	0.156
Flash pressure	10.619	3	3.54	7.309	0.005
Initial NaCl concentration	0.071	3	0.024	0.017	0.997

Table 9 shows the range analysis of heater energy consumption, and the range of each factor is 896.3, 9.437, and 486.712, respectively. Therefore, according to the range analysis table, heating temperature is the main factor affecting the heater energy consumption, initial NaCl concentration is a secondary factor, and flash pressure has the minimal influence. The analysis of variance in Table 10 reveals that the factors exhibit significance levels of 0, 1, and 0.356, respectively. Notably, heating temperature demonstrates the highest level of significance while flash pressure exhibits the least significant effect. Consequently, based on the variance analysis table, it can be concluded that heating temperature is the primary factor influencing heater energy consumption, whereas flash pressure has minimal impact. The results of variance analysis are consistent with the results of range analysis, the significance of flash pressure is 1, indicating that the energy consumption of the heater is only related to the heating temperature and the initial NaCl concentration, and the heating temperature has the greatest influence on the energy consumption of the heater.

According to the range analysis of energy consumption in vacuum pumps presented in Table 11, it is evident that each factor exhibits a range of 821.7, 782.1, and 42.9, respectively. Consequently, based on the range analysis table, it can be concluded that heating temperature primarily influences vacuum pump energy consumption while flash pressure acts as a secondary factor, and initial NaCl concentration exerts minimal influence. The analysis of variance in Table 12 reveals that the factors exhibit significance levels of 0.026, 0.047, and 0.999, respectively. Notably, the initial NaCl concentration demonstrates the highest significance level while heating temperature exhibits the lowest significance level. Consequently, based on the variance analysis table, it can be concluded that heating temperature is the primary factor influencing vacuum pump energy consumption, whereas the initial NaCl concentration has a minimal impact. The results of variance and range analysis are consistent: heating temperature has the greatest influence on the energy consumption

of vacuum pump. The reason is that when the flash pressure and the initial NaCl concentration are constant; the higher the solution heating temperature, the longer the flash duration, and the greater the energy consumption of the vacuum pump.

Table 8. Energy consumption data sheet.

Number	Q_h (kJ)	Q_y (kJ)	Q_{all} (kJ)	Q_x (kJ)
1	5814.4	3775.2	9589.6	7860.33
2	5348.3	3234	8582.3	9328.59
3	4777.1	3220.8	7997.9	7918.72
4	5388.9	2956.8	8345.7	10,981.18
5	5632.7	3247.2	8879.9	10,698.67
6	5847.75	2970	8817.75	11,757
7	5692.5	3484.8	9177.3	8267.84
8	5062.3	3194.4	8256.7	9174.11
9	5225.6	2706	7931.6	12,393.13
10	5520	3748.8	9268.8	7474.84
11	6159.6	3537.6	9697.2	9148.30
12	5996.1	3960	9956.1	7162.66
13	5535.9	3498	9033.9	7855.57
14	4931.2	2692.8	7624	11,551.52
15	5085.3	2376	7461.3	13,323.75
16	5224	2943.6	8167.6	9723.33

Table 9. Heater energy consumption range analysis table.

	Heating Temperature (°C)	Flash Pressure (kPa)	Initial NaCl Concentration (%)
K_{i1}	23,602.8	21,793.2	21,491.2
K_{i2}	22,408.55	21,828	20,820.4
K_{i3}	20,017.6	21,829.1	22,162.8
K_{i4}	21,212.7	21,791.35	22,767.25
k_{i1}	5900.7	5448.3	5372.8
k_{i2}	5602.137	5457	5205.1
k_{i3}	5004.4	5457.275	5540.7
k_{i4}	5303.175	5447.838	5691.812
R_i	896.3	9.437	486.712

Table 10. Heater energy consumption variance analysis table.

	Sum of Squares of Deviation	Degree of Freedom	Mean Square	F	Significance
Heating temperature	1,785,464.578	3	595,154.86	13.414	0
Flash pressure	329.548	3	109.849	0.001	1
Initial NaCl concentration	530,434.08	3	176,811.36	1.187	0.356

Table 11. Vacuum pump energy range analysis table.

	Heating Temperature (°C)	Flash Pressure (kPa)	Initial NaCl Concentration (%)
K_{i1}	14,520	13,398	12,922.8
K_{i2}	13,437.6	12,421.2	12,896.4
K_{i3}	11,233.2	14,427.6	12,777.6
K_{i4}	12,355.2	11,299.2	12,949.2
k_{i1}	3630	3349.5	3230.7
k_{i2}	3359.4	3105.3	3224.1
k_{i3}	2808.3	3606.9	3194.4
k_{i4}	3088.8	2824.8	3237.3
R_i	821.7	782.1	42.9

Table 12. Vacuum pump energy consumption variance analysis table.

	Sum of Squares of Deviation	Degree of Freedom	Mean Square	F	Significance
Heating temperature	1,496,928.5	3	498,976.17	4.432	0.026
Flash pressure	1,343,161.7	3	447,720.57	3.57	0.047
Initial NaCl concentration	4301.55	3	1433.85	0.006	0.999

According to the range analysis of total energy consumption in Table 13, it is evident that the respective ranges for each factor are 1718, 791.537, and 499.912, respectively. Consequently, based on the range analysis table, it can be inferred that the heating temperature exerts a primary influence on total energy consumption, while flash pressure serves as a secondary factor and initial NaCl concentration exhibits minimal impact. The analysis of variance in Table 14 reveals that the factors exhibit significance levels of 0, 0.533, and 0.846, respectively. Notably, the initial NaCl concentration demonstrates the highest level of significance while heating temperature exhibits the lowest level. Consequently, based on the variance analysis table, it can be concluded that heating temperature is the primary factor influencing total energy consumption, whereas initial NaCl concentration has a minimal impact. The results of variance and range analysis exhibit consistency, indicating that within the experimental range of working conditions, heating temperature exerts the most significant influence on total energy consumption, while initial NaCl concentration has the least impact. The effect of flash pressure lies between these two factors. This is attributed to higher heating temperatures leading to increased heater energy consumption, longer flash durations and consequently higher total energy consumption.

Table 13. Total energy consumption range analysis table.

	Heating Temperature (°C)	Flash Pressure (kPa)	Initial NaCl Concentration (%)
K_{i1}	38,122.8	35,191.2	34,414
K_{i2}	35,846.15	34,249.2	33,716.8
K_{i3}	31,250.8	36,256.7	34,940.4
K_{i4}	33,567.9	33,090.55	35,716.45
k_{i1}	9530.7	8797.8	8603.5
k_{i2}	8961.537	8562.3	8429.2
k_{i3}	7812.7	9064.175	8735.1
k_{i4}	8391.975	8272.638	8929.112
R_i	1718	791.537	499.912

Table 14. Total energy consumption variance analysis table.

	Sum of Squares of Deviation	Degree of Freedom	Mean Square	F	Significance
Heating temperature	6,551,953.1	3	2,183,984.4	13.758	0
Flash pressure	1,364,526	3	454,842.01	0.77	0.533
Initial NaCl concentration	534,850.72	3	178,283.57	0.27	0.846

The energy consumption per unit mass of vapor is an important index to measure the energy consumption required by the system. Table 15 shows that the range of each factor is 1911.84, 4440.19, and 653.835, respectively. Therefore, based on the range analysis table, flash pressure has the greatest impact on energy consumption per unit mass of vapor, heating temperature is a secondary factor, and initial NaCl concentration has the least influence. The analysis of variance in Table 16 reveals that the significance values for each factor are 0.529, 0, and 0.973, respectively. Notably, initial NaCl concentration exhibits the highest significance while flash pressure demonstrates the least significance. Consequently, based on the variance analysis table, it can be concluded that flash pressure is the primary factor influencing energy consumption per unit mass of vapor, whereas initial NaCl concentration has minimal impact. The results of variance and range analysis

are consistent. The significance of flash pressure is 0, and the significance of heating temperature is 0.529, indicating that these two factors have an important influence on the energy consumption per unit mass of vapor produced, and the initial NaCl concentration has little influence on the energy consumption per unit mass of vapor produced. The optimal operating conditions for achieving the lowest energy consumption per unit mass of vapor produced are as follows: a heating temperature of 99 °C, a flash pressure of 15 kPa, and an initial NaCl concentration of 20%.

Table 15. Table of range analysis of energy consumption per unit mass of vapor produced.

	Heating Temperature (°C)	Flash Pressure (kPa)	Initial NaCl Concentration (%)
K_{i1}	34,869.96	35,025.61	39,279.82
K_{i2}	36,828.27	41,009.59	37,120.09
K_{i3}	42,517.32	30,411.79	39,735.43
K_{i4}	40,403.99	48,172.55	38,484.2
k_{i1}	8717.49	8756.403	9819.955
k_{i2}	9207.068	10,252.397	9280.023
k_{i3}	10,629.33	7602.948	9933.858
k_{i4}	10,100.997	12,043.137	9621.05
R_i	1911.84	4440.19	653.835

Table 16. Table of variance analysis of energy consumption per unit mass of vapor produced.

	Sum of Squares of Deviation	Degree of Freedom	Mean Square	F	Significance
Heating temperature	8,909,988.011	3	2,969,996.004	0.777	0.529
Flash pressure	44,312,708.72	3	14,770,902.91	16.932	0
Initial NaCl concentration	985,712.578	3	328,570.859	0.073	0.973

In conclusion, based on the analysis of evaporation fraction and energy consumption per unit mass of vapor produced, it is evident that flash pressure plays a primary role in influencing both parameters, while heating temperature has a secondary impact, and initial NaCl concentration exerts the least influence. Under the operating conditions of 99 °C heating temperature, 15 kPa flash pressure and 20% initial NaCl concentration, the highest evaporation fraction and lowest energy consumption per unit mass of vapor are achieved. Therefore, this combination represents the optimal working condition determined by orthogonal experiment.

4.2.2. Static Flash Control Variable Experiment

Figure 7 shows the effect of heating temperature on evaporation fraction and energy consumption per unit mass of vapor produced. The results indicate that, under constant flash pressure and initial NaCl concentration, the evaporation fraction increases with rising heating temperature; however, the energy consumption per unit mass of vapor produced initially increases and then decreases. Figure 8 shows the effect of flash pressure on evaporation fraction and energy consumption of vapor per unit mass produced. The results demonstrate that, under constant heating temperature and at the initial NaCl concentration, the evaporation fraction increases, and the energy consumption per unit mass of vapor produced is reduced as the flash pressure decreases.

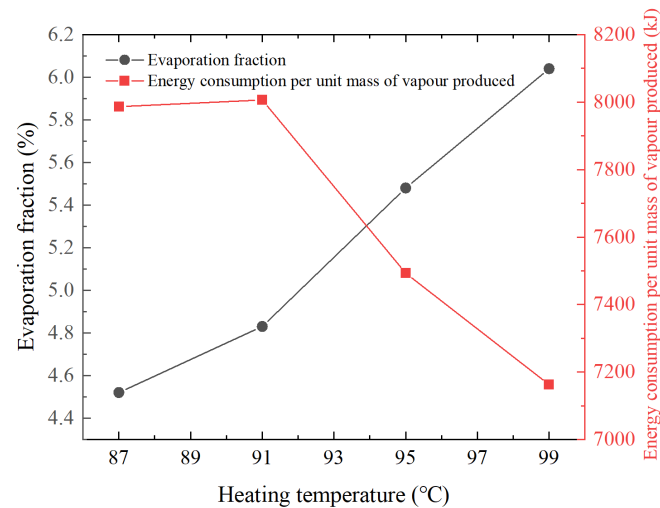


Figure 7. The effect of heating temperature on evaporation fraction and energy consumption of vapor per unit mass produced.

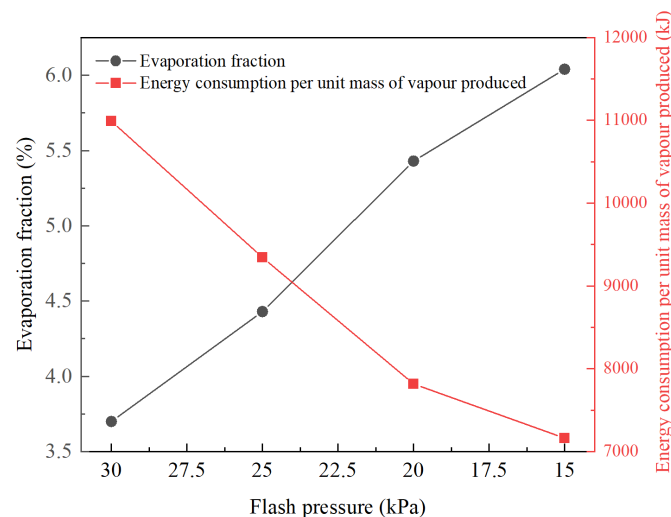


Figure 8. The effect of flash pressure on evaporation fraction and energy consumption of vapor per unit mass produced.

5. Conclusions

In order to develop engineering applications of the circulatory flash evaporation system, this study conducted a simulation investigation on circulatory flash evaporation and an experimental analysis on static flash evaporation using a NaCl solution with a heating temperature ranging from 87 °C to 99 °C, a flash evaporation pressure ranging from 30 kPa to 15 kPa, and an initial NaCl concentration ranging from 10% to 25%. The following conclusions were derived.

The results of the circulatory flash evaporation simulation study indicated that an increase in heating temperatures, a decrease in flash pressures and higher initial NaCl concentrations could enhance the treatment efficiency of high-salt wastewater. The flow rate of the vapor outlet was primarily influenced by the heating temperature and flash pressure, demonstrating an increase with an elevated heating temperature and a decrease with escalating flash pressure. The outlet flow rate of crystallized salt was primarily influenced by the initial concentration of NaCl, whereby an increase in the initial NaCl concentration resulted in a corresponding augmentation in the rate of efflux for crystalline salt.

The results of the orthogonal experimental study on static flash evaporation revealed that the pressure of flash evaporation exerted a primary influence on both evaporation

fraction and energy consumption per unit mass of vapor produced, with heating temperature serving as a secondary factor, and the initial NaCl concentration exhibited minimal impact. The optimal experimental conditions were achieved at a heating temperature of 99 °C, a flash pressure of 15 kPa, and an initial NaCl concentration of 20%. Experimental investigation of the control variables of static flash evaporation demonstrated that, when maintaining a constant flash pressure and initial NaCl concentration, an elevation in heating temperature resulted in an augmented evaporation fraction and a reduction in energy consumption per unit mass of vapor produced. Similarly, when the heating temperature and initial NaCl concentration were kept constant, a decrease in flash pressure resulted in an increased evaporation fraction and reduced energy consumption per unit mass of vapor produced.

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