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Research on enhanced coagulation test for sludge water recycling in water treatment plant in Ganjiang River Nanchang Section

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ABSTRACT

With raw water from Ganjiang River Nanchang Section as the research object and dosage, sludge water reflux ratio and reflux concentration as the control parameters, coagulation reflux and orthogonal test is designed to measure water quality indicators of the unfiltered water such as turbidity, chemical oxygen demand (COD_{Mn}), partial metal concentration and total bacterial count. The test demonstrates that: sludge water reflux may enhance the coagulation, promote the quality of the precipitated water and save dosage. Within a certain range, the lower the dosage, the more obvious the effect of enhanced coagulation; the best result was obtained under the low concentration mud water (turbidity of 40–50 NTU) reuse conditions, with the 10% return ratio and the dosing rate of 10 mg/L; there is a certain linear relationship between the sludge water concentration and the recycling amount, that is, the product of them is stable within a certain range; the analysis shows that COD_{Mn}, ammonia nitrogen, total phosphorus, partial metal concentration, the total bacterial count and fecal coliforms of the sedimentation basin effluent will not increase significantly by reasonable control of the reflux parameters when returning high concentration sludge water (turbidity is about 500 NTU), the overall risk of subsequent reuse is manageable and there are no safety issues. COD_{Mn} is the lowest when the reflux ratio is between 4% and 6%, ammonia nitrogen and total phosphorus are both at their lowest when the reflux ratio is between 2% and 4%, When the reflux ratio is controlled at 4%, the total bacterial and fecal coliform counts are prevented from increasing too rapidly and there is no significant accumulation of Al, Fe and Mn in the effluent. The orthogonal experiment shows that for turbidity removal, the dosage plays a major role, and the reuse of sludge water can further strengthen coagulation on this basis. The research results can provide certain theoretical and data references for the sludge water reflux system in water treatment plants in the Ganjiang River Nanchang Section.

Keywords: Water treatment plant sludge water; Dosage; Reflux ratio; Reflux safety

1. Introduction

The wastewater produced by the water treatment plant includes sludge water from the sedimentation tank and backwash water from the filter, accounting for about 6%–10% of the total water consumption of the plant [1]. The sludge water contains a large amount of gravels, suspended solids, heavy metals, organic matter and residual coagulant [2], which is discharged into the natural environment directly and damages the ecological environment [3]. At the same time, recycling the residual coagulant and other effective constituents contained in the sludge water can save resources and protect the environment. The research results indicate that [4–6]: recycling of appropriate sludge water in proper concentration may enhance the coagulation, increase the water quality and reduce the dosage. However, in actual

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production, water plants still lack the corresponding safety measures that are appropriate for the potential water quality risks after a backflow of the wastewater, due to the lack of corresponding theoretical research and scientific data support, coupled with the lack of professional technical force on-site and other practical factors. There is still greater blindness and arbitrariness in the selection of key parameters such as the reflux method, reflux concentration, and reflux flow; the control of the dosage and the reflux system cannot be adjusted according to the water quality of different water sources on site. With the sludge water as core, the research focuses on the following aspects: a study of the dynamic relationship between sludge water reflux concentration and reflux volume by mixed beaker experiments under different dosages; measurement of the effluent quality to evaluate the safety of the sludge water recycling; orthogonal test for determining priority of the reflux ratio and dosage in affecting recycling.

2. Materials and methods

2.1. Quality of raw water and sludge water

The test water is from the Ganjiang River, the sludge water from the bottom of a sedimentation tank of a water plant in Nanchang. General condition for the quality of raw water and sludge water in the test period are shown in Table 1.

2.2. Test coagulant

The coagulation process involves comprehensive functions of physics, chemistry, physical chemistry, hydraulics, colloid chemistry and other aspects. Polyaluminum chloride (PAC) is currently the most widely used inorganic polymer coagulant and drinking water treatment agent. It has a small effect on the pH of the effluent, its dosage is less than other coagulants, and the amount of sludge produced is also less, with good performance in turbidity removal [7–9]. Besides, it has a certain removal effect on high chroma, low temperature and low turbid water, with the flocs settled quickly and easily, as well as a low market price. Therefore, PAC is used as a coagulant in this test. PAC used is produced by Jiangxi Pengteng Industry Co., Ltd., (China) with Al_2O_3 mass fraction of 0.3, the basicity of 0.834 and pH value of 3~5.

2.3. Test method

The optimal dosage of the day is determined first in the test. On this basis, the sludge water with certain turbidity is recycled and added to the 1 L coagulation beaker in a reflux ratio of 0%, 2%, 4%, 6%, 8%, and 10%. The sludge water is naturally settled after being collected, and then the turbidity meter and the bottom mud after sedimentation are used to formulate five groups of test turbidity under different concentration (characterized by turbidity) gradients: 40–50 NTU, 90–100 NTU, 140–150 NTU, 190–200 NTU and high concentration 500 NTU. Starting from the optimal dosage, the dosage is reduced in turn, and a group of beaker test is conducted in one day to determine the effluent turbidity after sedimentation to determine the effluent effect; then Al, Fe, Mn, total bacterial count, fecal coliforms, ammonia nitrogen, total phosphorus and chemical oxygen demand (COD_{Mn}) of the effluent are measured to explore the safety of the sludge water recycling; finally, a two-factor three-level orthogonal test is designed on the basis of the dosage and reflux ratio to determine turbidity, chroma and UV_{254} of the effluent and figure out sequential orders in affecting the effluent quality. Testing indexes and methods are shown in Table 2.

3. Results and discussion

3.1. Beaker coagulation test

The coagulation mixing time of the agitator in the coagulation mixing test is set to 15 min, wherein the speed in the rapid mixing stage is 400 rpm, and the rapid mixing time is 15 s. The middle stage of flocculation is divided into three sections, with the rotational speeds of 200, 160 and 80 rpm respectively, and the time of 4, 5 and 6 min respectively. The test results for each section are shown in Figs. 1–5.

The optimal dosage of raw water coagulation on the day is 11 mg/L. Fig. 1 shows that under the low concentration of sludge water (with a turbidity of 40–50 NTU), with the increase of reflux ratio, there is a good removal effect on the turbidity of the effluent. Under the low dosage, the recycling effect of the sludge water is more obvious, with the turbidity less than 3 NTU in all cases. The optimal effect occurs at a 10% reflux ratio and 10 mg/L dosages. As recycling of excessive sludge water will have an effluent safety risk in actual production, the test only considers the maximum reflux ratio to be 10%.

The optimal dosages are 9, 10, 10 and 9 mg/L respectively and the test results are shown in Figs. 2–5.

Figs. 2–4 show that in the case of turbidity of 90–200 NTU, the dosage is the optimal dosage of the day, indicating that the recycling of the sludge water has little effect on the turbidity of the effluent. Under the same dosage, the increased reflux ratio of the sludge water does not improve the effluent effect significantly, but leads to increased effluent turbidity. During the recycling of 90–200 NTU sludge water, suspended solids and colloids in the water have been condensed into large micelles under the action of the coagulant. Sludge water only plays an auxiliary role rather

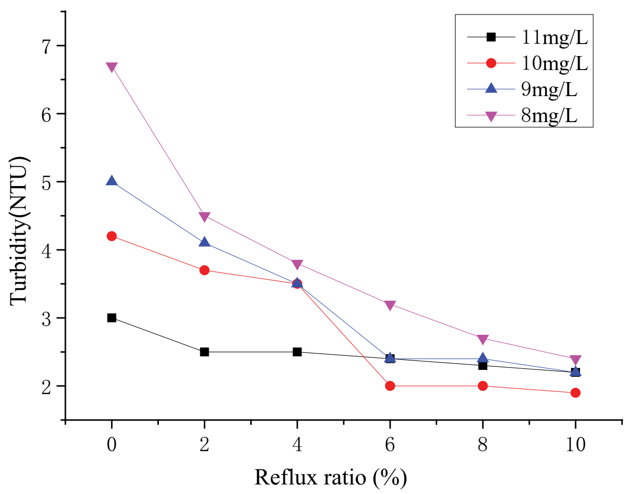

Fig. 1. Turbidity of effluent from 40~50 NTU sludge in different dosages and reflux ratios.

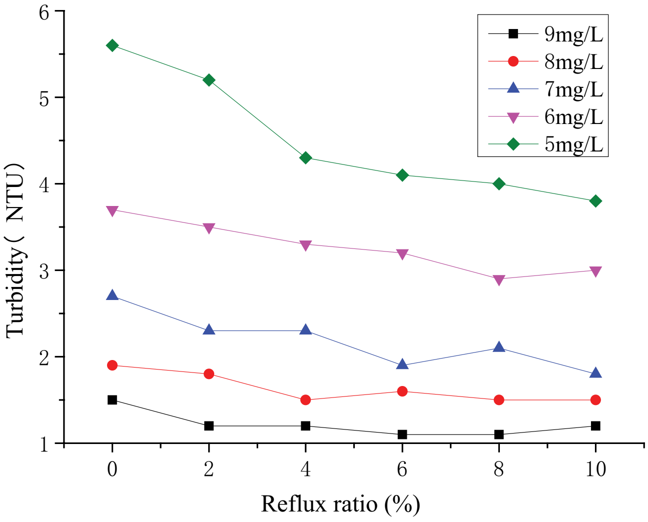

Fig. 2. Turbidity of effluent from 90~100 NTU sludge in different dosages and reflux ratios.

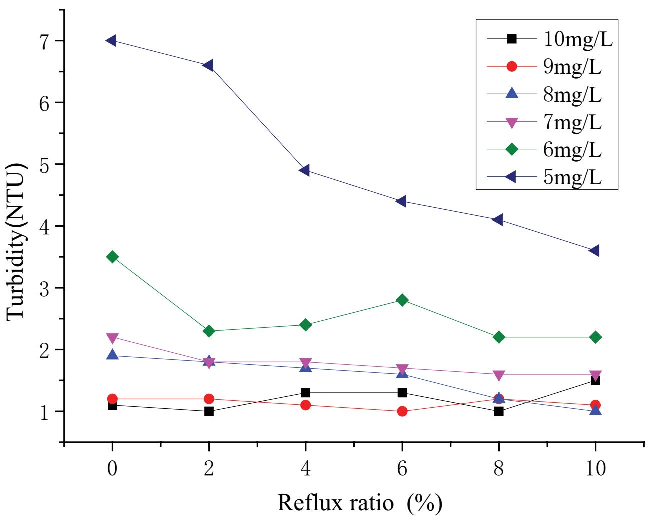

Fig. 3. Turbidity of effluent from 140~150 NTU sludge in different dosages and reflux ratios.

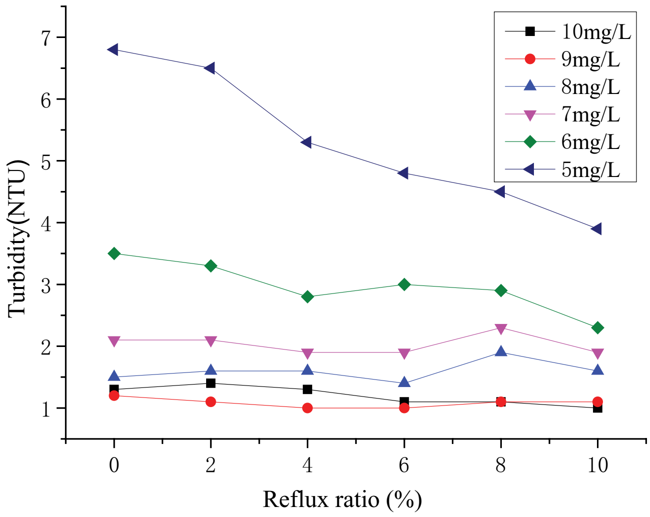

Fig. 4. Turbidity of effluent from 190~200 NTU sludge in different dosages and reflux ratios.

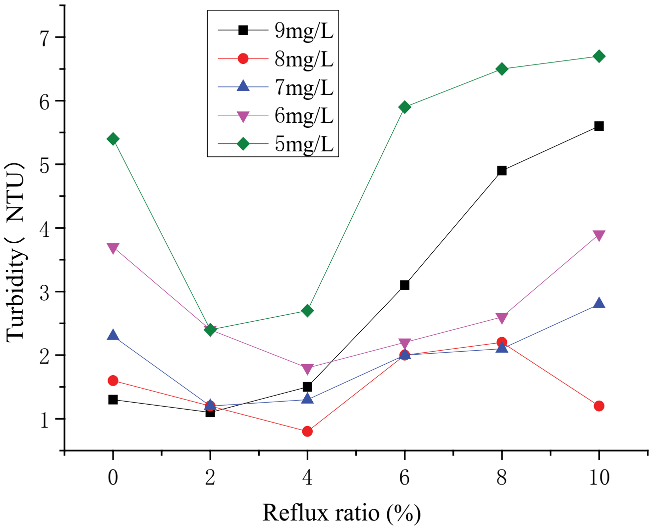

Fig. 5. 500 NTU turbidity curve of reclaimed effluent in different dosages and reflux ratios.

than the leading role. However, the sludge can be precipitated quickly, so the recycling of 90–200 NTU sludge water will not have much impact on the effluent results. On the contrary, in the case of low dosage, recycling of the sludge water may exert a synergistic coagulation effect along with the PAC, thus saving the dosage. In actual production, considering the turbidity of the effluent only, recycling of 90–200 NTU sludge water can reduce the dosage, thus the sludge water can exert a synergistic coagulation effect.

Fig. 5 shows that during recycling of the sludge water with a turbidity of 500 NTU, under the same dosage, as the reflux ratio increases, the turbidity of the effluent first decreases and then rises, indicating there is a knee of the curve. The optimal reflux ratio for recycling is 2%–4%. As the reflux ratio increases, the water quality of the effluent will deteriorate. With the decrease in the dosage, such deterioration trend will be more obvious. The reason is that, as the increase of the sludge water volume, a large amount of sediment and suspended matter carried are distributed in the water body, thus increasing the suspended colloid. As the added coagulant and the aluminum salt in the sludge water cannot lower the zeta potential [10], the suspended solids cannot accumulate for sedimentation, thus reducing the effluent quality.

Summarized results of the optimal operating points for each group of tests are shown in Table 3.

The above table shows that low turbidity sludge water reflux requires a high reflux ratio, whereas a low reflux ratio is required. The product of the sludge water turbidity and the reflux ratio at the optimal operating point is stabilized within a certain range, that is, there is a certain dynamic relationship between the product of the sludge water concentration C and the reflux quantity Q. This conclusion can be roughly referred to for the subsequent pilot-scale test and the

Ganjiang River water (Nanchang Section water plant) on the reflux data, namely: the reflux ratio of the sludge water can be roughly determined according to the sludge water concentration on the day (characterized by turbidity).

3.2. Experimental study on water quality safety of reflux high concentration sludge water

In order to investigate the safety of the effluent after sedimentation, the high concentration sludge water was specially selected for analysis. We select the muddy water with a turbidity of 500 NTU and a dosage of 7 mg/L to detect the COD_{Mn}, total bacteria, Al content, Fe content, Mn content, ammonia nitrogen, total phosphorus and fecal coliforms of the reflux effluent, the test results are shown in Figs. 6–11.

Fig. 6 shows that in the case of a 2%–4% reflux ratio, the COD_{Mn} decreases significantly and reaches the minimum value at 4%–6% ratio. When the reflux ratio is more than 6%, the COD_{Mn} increases again. As under low reflux ratio, the sludge water recycling can enhance the coagulation and the colloidal particles condensed can absorb the macromolecular organic matters in the water. With a high reflux ratio, the macromolecular organic matters contained in the sludge water are released passively due to the complexation among colloids, suspended particles and metal ions in the water [11], thus increasing COD_{Mn}. Therefore, with such reflux conditions, a 4%–6% reflux ratio may guarantee effective control of the effluent COD_{Mn}. After recycling, the total bacterial count in the effluent rises with the increase of the reflux ratio, and this phenomenon is particularly obvious under the reflux ratio above 6%. As in the course of coagulation, bacteria are mainly removed by attachment to macromolecular particles or suspended matters. With a low reflux ratio, the total bacterial count in the water will not increase sharply during re-wrapping of the recycling. With the excessive reflux ratio exceeding its capacity to wrap, the probability of attached bacteria being released into the water will rise, thus increasing the total bacterial count. A reflux ratio of less than 6% may control the total bacterial count of the precipitated water.

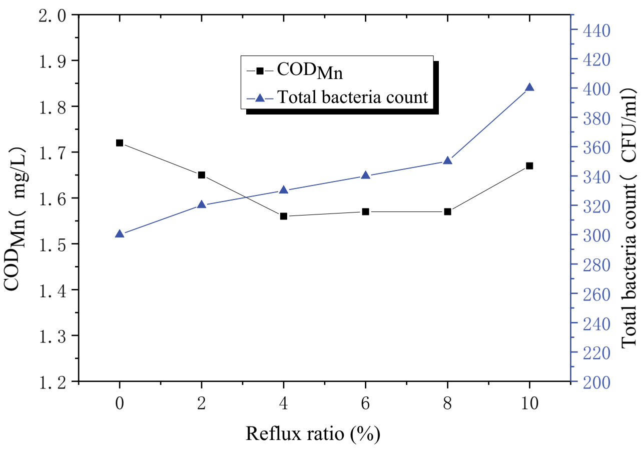

Fig. 6. Effects of different reflux ratios on the COD_{Mn} and bacteria in sedimentation effluent.

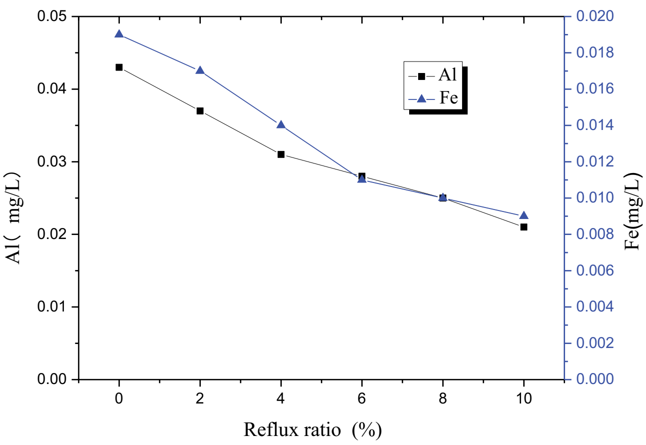

Fig. 7. Effects of different reflux ratios on the Al and Fe in sedimentation effluent.

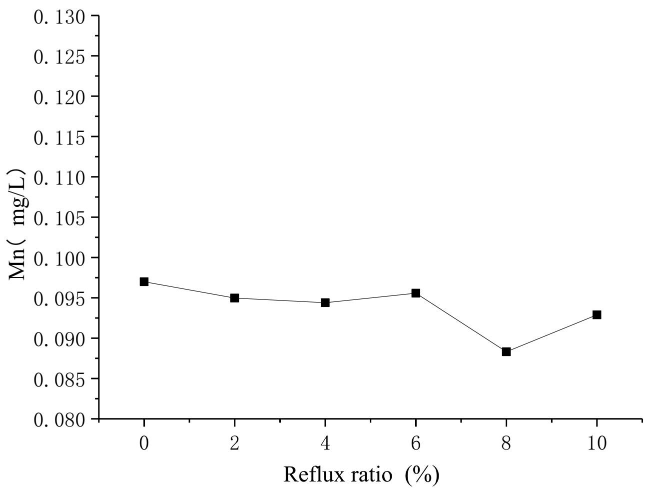

Fig. 8. Effects of different reflux ratios on the Mn in sedimentation effluent.

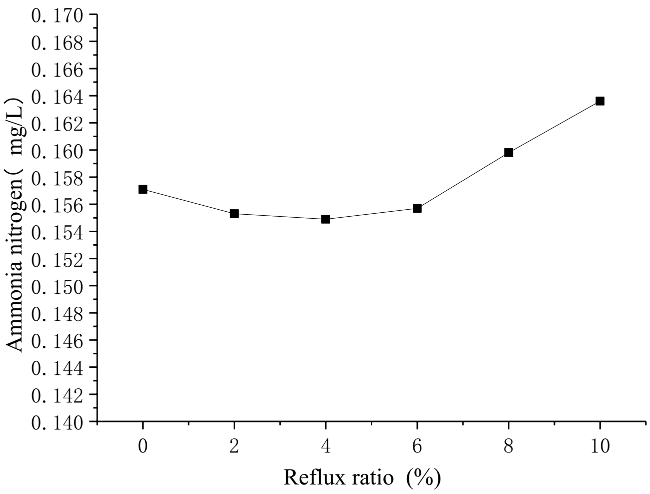

Fig. 9. Effects of different reflux ratios on the ammonia nitrogen in sedimentation effluent.

Fig. 7 shows that the PAC is applied to the raw water as the coagulant, increasing Al content in the water body. Al is also contained in the recycled sludge water, but the Al content in the precipitated effluent does not rise. It is because, after recycling the sludge water, Al exists in the colloidal form or free form in the water. The free Al upon recycling can be combined with the suspended solids in the raw water to make the floc denser and easier to precipitate [12], and will not cause an increase of the Al content [13]. Fe content does not rise significantly, since its content is originally low in the water and it is present in the form of solid particles. The recycling of sludge water increases the aluminum hydroxide colloid concentration in the water. As the solubility of ferric hydroxide is lower than that of aluminum hydroxide, ferric hydroxide precipitates will be generated easier, thus making no increase of Fe content.

Fig. 8 shows that with the increase of reflux ratio of sludge water, there is no obvious accumulation trend of Mn, and the specific reason is similar to that of Fe. With the increase of reflux ratio, there is no obvious enrichment process of Al, Fe and Mn, and there is no safety risk of water effluent. In general, the reflux of sludge water has no obvious effect on the enrichment of metal elements.

Fig. 9 shows that the backflow of the sludge water has no good effect on the ammonia nitrogen removal. The concentration of ammonia nitrogen in the sedimentation effluent rises as the reflux ratio increases. The possible reason is

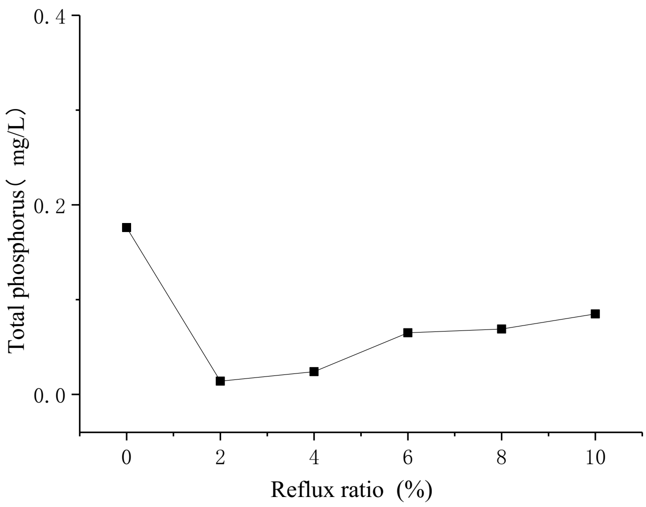

Fig. 10. Effects of different reflux ratios on the total phosphorus in sedimentation effluent.

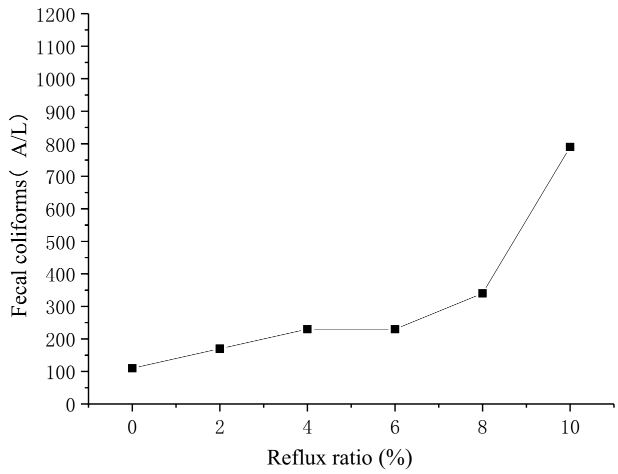

Fig. 11. Effects of different reflux ratios on the fecal coliforms in sedimentation effluent.

Table 1
The quality of raw water in Ganjiang River and sludge water

Index	Ganjiang River	Water sludge
Turbidity (NTU)	10–160 NTU	400–2,000 NTU 12–37 NTU (supernatant)
Chroma (CU)	7–18 CU	17–34 CU
pH	7.1–7.5	7.2–7.9
NH_3–N (mg/L)	0.05–0.11 mg/L	0.38–0.86 mg/L
COD_{Mn} (mg/L)	1.5–4.3 mg/L	7.0–11.2 mg/L
UV_{254} (cm^{-1})	0.025–0.068 cm^{-1}	0.127–0.185 cm^{-1}
Total phosphorus (mg/L)	0.02–0.19 mg/L	0.29–1.17 mg/L

Table 2
Testing indexes and methods

Detection index	Method	Instrument and equipment
Turbidity		Hach 2100AN Desktop Turbidimeter
Chroma		Hach DR6000 Ultraviolet Spectrophotometer
UV_{254}		Hach DR6000 Ultraviolet Spectrophotometer
Ammonia nitrogen		Hach DR6000 Ultraviolet Spectrophotometer
Total phosphorus		Hach DR6000 Ultraviolet Spectrophotometer
COD_{Mn}	Acid potassium permanganate method	
Total bacteria count and fecal coliforms	Testing in accordance with Water and Wastewater Monitoring and Analysis Method (4th edition)	
Al, Fe, Mn		Varian 720-ES Inductively Coupled Plasma Emission Spectrometer

Table 3
Statistics of optimum working conditions for sludge water reuse in each group

Turbidity of reused sludge water (NTU)	Dosage (mg/L)	Reflux ratio at optimum working conditions (%)	Product range of turbidity of sludge discharge water and return ratio at optimum operating point
40~50	8,9,10,11	10	4.5~5
90~100	5,6,7,9,11	10	9~10
140~150	6,7,9,10	8	11.2~12
190~200	7,8,9,10	6	11.4~12
500	6,7,9	2	10

Table 4
The result of orthogonal experiment

Orthogonal test						
Experimental sequence	Experimental factors		Experimental result			
	Dosage (mg/L)	Reflux ratio (%)	Turbidity after settling (NTU)	Chroma after settling (CU)	UV_{254} after settling (m^{-1})	Turbidity removal rate (%)
1	6	2	2.4	6	5	80.00
2	6	6	2.1	5	4.6	82.50
3	6	10	1.7	4	4.6	85.83
4	8	2	1.6	4	4.4	86.67
5	8	6	1.1	2	4.3	90.83
6	8	10	1.4	3	4.5	88.33
7	10	2	1.2	2	4	90.00
8	10	6	1.1	3	4.4	90.83
9	10	10	1	3	4.5	91.67
K_1	82.78	88.61	90.83			
K_2	85.56	88.06	88.61			
Range R	8.05	3.05				

Notes: K is the average value of the corresponding turbidity removal rate at different levels of factor; the range R is the difference between the maximum K value and the minimum K value of each factor.

that there may be a certain sludge dead angle in the sludge discharge area of the reaction tank, the sludge at the bottom will be decomposed, and the microbial degradation will produce a large amount of ammonia nitrogen dissolved into the sludge water newly entering the sludge hopper, so that the content of ammonia nitrogen in the sludge water returning to the water inlet will continue to increase, and with the increase of reflux ratio, the ammonia nitrogen content in the effluent after sedimentation will also increase, which will increase the amount of chlorine in the disinfection process [14]. It can be considered that appropriate preoxidation measures should be added in the subsequent reflux process improvement to make the sludge water contain a certain amount of dissolved oxygen before reflux, so as to reduce the influent concentration of ammonia nitrogen in the sludge water reflux.

Fig. 10 shows that the reflux of sludge water can greatly reduce the total phosphorus content in water. The main reason for this is that the chosen coagulant PAC produces a large amount of aluminum-containing sludge, which has a good adsorption effect on phosphorus because of its large specific surface area and porosity [15], and the large amount of Al^{3+} and PO_4^{3-} dissolved in water will be easy to form $AlPO_4$ precipitation. At the same time, due to the reflux of sludge water, there are a lot of suspended solids in the water, which can quickly form a large agglomerated core and could precipitate collaboratively with the phosphate to remove phosphorus in the water without a decrease in pH.

Fig. 11 shows that the changing trend of fecal coliforms is similar to that of the total bacterial count. At reflux ratios below 6%, the increase of fecal coliforms in the water body was not significant, rising from 110 L without reflux to 230 L at a 4% reflux ratio. When the reflux ratio is more than 8%, the number of fecal coliforms also increased by multiples, increasing to 790 L.

3.3. Orthogonal test

In actual production, the turbidity of the discharge water is an uncontrollable factor, while the dosage of coagulant and the reflux ratio of the discharge water can be effectively adjusted according to the turbidity of the discharge water to control the turbidity of the effluent after reflux. Therefore, in order to further determine the primary and secondary relationship between them, a two-factor three-level orthogonal test was designed on both of them. The turbidity of the reused discharge water is controlled at 200 NTU. Because in practical engineering applications, the turbidity is usually controlled below 200 NTU, so 200 NTU is used as an example for illustration. With sludge water turbidity 200 NTU, the best daily dosage is 11 mg/L, using the raw water with a turbidity of 12 NTU, chroma of 9 CU and UV_{254} of 5.6. The test dosage, reflux ratio and test results are shown in Table 4.

Table 4 shows that sludge water recycling has a significant effect on the removal of turbidity. However, the dosage plays a more important role, and the effect of sludge water recycling is limited. Similar to turbidity, removal of the chroma is also obvious. But it has a poor effect on the removal of UV_{254}. It can be concluded that sludge water recycling can enhance coagulation, and has a good effect on the removal of the turbidity and chroma of the water body.

Results of the orthogonal test show that the magnitude of the range *R* can determine the property of various factors. A larger *R*-value indicates a huger influence on the test results. Therefore, in terms of the removal rate of the turbidity, the priority of the dosage is obviously greater than that of the reflux ratio of sludge water. Sludge water recycling only assists the coagulant to enhance the coagulation effect, and the coagulant still plays a major role in the course of coagulation.

4. Conclusion

The sludge water recycling beaker test and orthogonal test show that sludge water recycling may enhance the coagulation, promote quality of the precipitated water and save dosage, especially in a low dosage. It is preliminarily concluded that there is a linear relationship between the sludge water concentration (characterized by turbidity) and sludge water reflux volume (characterized by reflux ratio): low turbidity sludge water reflux requires a high reflux ratio, whereas a low reflux ratio is required. Their product is in a certain interval, which can be used for reference in the actual production of water plants. Measurement of COD_{Mn}, ammonia nitrogen, total phosphorus, Al, Fe, Mn, total bacterial count, fecal coliforms of the precipitated water after reflux high concentration sludge water (turbidity is about 500 NTU) indicates that overall risks are controllable without safety problems. The orthogonal test shows that dosage plays a major role in the removal of turbidity, while the sludge water recycling may be further enhanced on this basis.

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