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Effect of sludge return ratio on the treatment characteristics of high-efficiency sedimentation tank

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ABSTRACT

An advanced treatment experiment on secondary effluent water of the municipal wastewater treatment plant by utilizing a high-efficiency sedimentation tank was conducted. The removal efficiencies of suspended solids (SS), total phosphorus (TP) and chemical oxygen demand (COD) as well as the characteristics of sludge settling under different sludge reflux ratios were studied. In addition, the optimal working conditions were analyzed in this experiment. The experimental results show that sludge reflux ratio plays an influential role in contaminant removal and sludge settling. In case the reflux ratio is 50%, concentrations of SS, TP and COD in effluent water are 10, 0.48 and 49 mg/L, respectively. The effluent water is up to Grade 1A of the Standard (GB18918-2002), and the sludge can be settled well. The high-efficiency sedimentation tank presented a remarkable effect in removing suspended particles, as suspended substances with particle diameters above 3 μm could be removed effectively and those with particle size(s) of or above 12 μm could be completely removed. Experimental results show that the adoption of high-efficiency sedimentation tank significantly improves the treatment effects of SS, TP and COD in sewage. The experimental parameters acquired under the optimal working conditions can be served as references for the actual running of high density sedimentation tank in the municipal sewage treatment plant.

Keywords: High-efficiency sedimentation tank; Sludge reflux ratio; Suspended substance; Sludge settling

1. Introduction

In recent years, water scarcity has become more and more serious. On the one hand, water has been contaminated by some new persistent pollutants; on the other hand, water is needed more than ever as people's living standard is improved [1]. Lack of rain and strong evaporation aggravate water shortage in irrigation and other industries demanding large quantity of water especially in summer, for which new requirements for advanced wastewater treatment and wastewater reuse are put forward [2]. Although conventional secondary treatment can remove 40–60% of chrominance, 80–90%

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of BOD and 90% or more of chemical oxygen demand (COD) in municipal wastewater, removal rates of ammonia nitrogen and phosphorus by this method are rather low [3]. Besides, small or trace amount of hard degradation organic pollutants in water cannot be removed by the conventional secondary treatment [4], which makes it difficult for secondary effluent water to meet the Grade 1A of water quality standards specified in *Discharge standard of pollutants for municipal wastewater treatment plant* (GB18918-2002) and wastewater reuse standards. The standard values are shown in Table 1. By employing enhanced biological treatment for nutrient and phosphorus removal once in conventional secondary treatment, the indexes of organic compounds, total nitrogen and ammonia meet the requirements of Grade 1A of the Standard, but indexes of SS and TP in the effluent water fail to meet emission standards. Therefore, it is necessary to treat the secondary effluent water through subsequent advanced physical and chemical processes to remove suspended solids (SS) and total phosphorus (TP) so as to ensure the reliable and standardized emission. The commonly used advanced treatment process is mainly focused on mature coagulation sedimentation—filtration. By adopting coagulation–sedimentation process, the turbidity, chrominance and other sensory indexes of raw water can be reduced, and a variety of macromolecule organics and some heavy metals can be removed. However, the turbidity of urban sewage secondary effluent is mainly due to the low concentrations of colloids and zoogloea particles in the treatment process, which makes it difficult to form floc with sound settling properties in coagulation process and a more efficient flocculant is required. Moreover, the adaptability of treated water is rather poor [5]. Degremont Company in France has developed a new type high-efficiency sedimentation tank to qualify the effluent water that failed to meet higher water quality requirements as conventional secondary treatment and ordinarily advanced treatment are ineffective. The high-efficiency sedimentation tank integrating coagulation, sedimentation and enrichment processes is mainly comprised of a mixing zone, a reaction zone and a sedimentation/enrichment zone [6]. By adding polymer flocculant polyacrylamide (PAM), flocs with good settling properties can be produced and a higher treatment efficiency of SS, COD and TP can be achieved [7]. Therefore, the above wastewater treatment process, which is compact, efficient and flexible, can be used for treating industrial and domestic wastewater, drinking water and rainwater [8]. Moreover, the effluent water quality is rather good. Consequently, this new water treatment process has been widely adopted in France, Germany and some other European countries [9]. Owing to the advantages of the high-efficiency sedimentation tank which conventional treatment processes are lack of, the tank has been employed in some domestic wastewater treatment projects including Shidunzi mountain water plant expansion project in Urumqi, Qiaoxi sewage treatment plant wastewater reuse renovation project in Shijiazhuang City and Shougang sewage treatment project [10].

The main purpose of this study is to reduce SS and TP in treated water to improve the quality of effluent water. This study could solve the problem that SS and TP values of conventional process effluent cannot meet the requirements of the Grade 1A of water quality standards.

Table 1
Discharge standard of pollutants for municipal wastewater treatment plant (unit: mg/L)

Basic control	Grade 1		Grade 2	Grade 3
Items	A	B		
COD	50	60	100	120
SS	10	20	30	50
TN	15	20	–	–
Ammonia Nitrogen	5	8	25	–
TP	0.5	1	3	5

2. Experimental device and methods

2.1. Experimental water quality

The raw water used in this study was the intermediate water, after two hours of precipitation, taken from the intermediate tank, in which the influent water had been processed through bio-contact oxidation, in the intermediate water station of Shandong Jianzhu University. The indicators of experimental raw water quality are shown in Table 2.

Table 2
Experimental raw water quality

Indicator	Raw water
Temperature (℃)	5.2–27.5
pH	7.0–7.95
SS (mg/L)	23.5–71.67
TN (mg/L)	43.11–51.25
Ammonia nitrogen (mg/L)	22.75–31.42
TP (mg/L)	0.49–3.90
COD (mg/L)	131.36–284.2

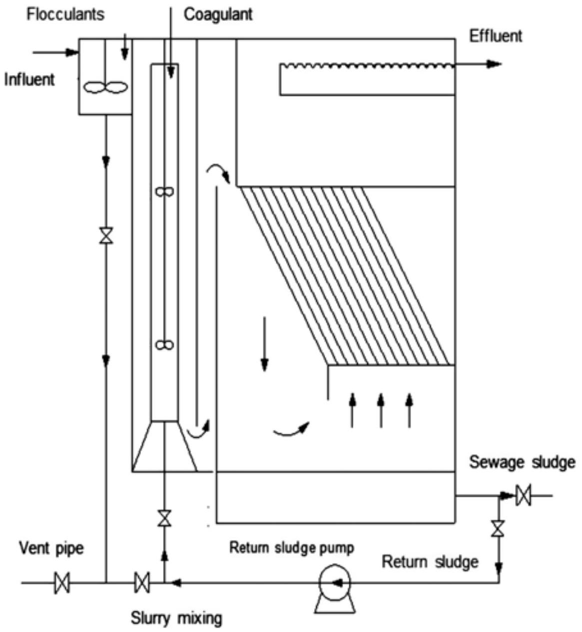

Fig. 1. Schematic diagram of high-efficiency sedimentation tank.

2.2. Experimental device

The experimental device is self-designed and manufactured by Shanghai Daming Education Instrument Co., Ltd. The experimental device of high-efficiency sedimentation tank is shown in Figs. 1 and 2. The device, with a designed flow rate of 120 L/h, is made of plexiglass and fixed onto a stainless steel shelf. The entire pilot device comprises three parts: the mixing zone, the reaction zone and the inclined-plate sedimentation/condensation zone. The mixing zone is where the water and coagulant are uniformly mixed at high speed. The reaction zone is mainly for slow-speed combination reaction among influent water, return sludge and coagulant. In the inclined plate sedimentation/condensation zone, high-efficiency inclined plate sedimentation guarantees a high-rise velocity in the sedimentation zone to promote the adsorption and precipitation of floc produced in the reaction zone. Detailed design parameters of pilot devices are shown in Table 3.

Fig. 2. Installation diagram of a laboratory scale high-efficiency sedimentation tank.

3. Results and discussion

Previous research shows that appropriate flow rate for sludge recycle improves the utilization efficiency of coagulant and flocculant enriched in the sewage sludge, so as to reduce their dosage [11–13], and increase the concentration of particles in water, which can make aggregation and sedimentation of particles easier and further improve the sludge settling effect [13]. Thus, sludge reflux ratio has a great impact on the operation efficiency and stability of the high-efficiency sedimentation tank. Therefore, it is of great importance to maintain and operate the high-efficiency sedimentation tank in a proper sludge reflux ratio.

Before this experiment, a static orthogonal experiment was carried out to determine the optimal dosage of PAM, coagulant type and dosage as well as mixing

Table 3
Design parameters of pilot devices (unit: mm)

Item	Design parameters of pilot devices
Mixing tank	120 × 120 × 150 (length × width × height)
Coagulation reaction tank	120 × 150 × 900 (length × width × height), internal diameter of draft tube is 60 mm
Inclined-plate sedimentation tank	120 × 500 × 1,000 (length × width × height)
Sludge reflux device	The pump model for sludge recycling is MP-15RN
Dosing device	The pump model for dosing is CONC0803PP1000A001

speed. According to the results of orthogonal experiment, the best combination of experimental parameters was chosen as the condition of subsequent experiments. The operational parameters of the pilot device are as follows: the flow rate of influent is 120 L/h, the concentration of $FeCl_3$ used as the coagulant is 10.26 mg/L (measured in Fe^{3+}) and the concentration of PAM used as the coagulant aid is 0.80 mg/L. The operational parameters of mixing equipment are as follows: stirring speeds of the mixed tank and the reaction tank are 120 and 80 r/min, respectively. Seven working conditions (0, 33, 50, 67, 83, 100 and 133%) are set to conduct the comparative tests by changing the sludge reflux ratio. After 35 min, since the pre-flocculation starts, water samples are taken every 10 min, and 11 water samples have been obtained totally. The measurement indicators for evaluation are SS, TP, COD, SC (sludge concentration), SV (settling velocity) and SVI (sludge volume index).

3.1. The effect of different sludge reflux ratios on pollutants removal

The results of SS removal in the effluent water under different sludge reflux ratios are shown in Fig. 3.

Fig. 3 shows that the SS values of effluent water declines with the test time, indicating that SS can be removed to some extent under different sludge reflux ratios. As the results, when the sludge reflux ratios are 50 and 67%, the SS values of effluent water are 10 and 8 mg/L, respectively, and the removal efficiency reaches 73.19 and 65.96%, satisfying the requirement of Grade 1A of *Discharge standard of pollutants for municipal wastewater treatment plant* (GB18918-2002).

The effluent water quality is significantly higher than that under other sludge reflux ratios. The reason is that the function of the return sludge is to increase the content of particles and enhance flocculation, while the SS removal mainly relies on the adsorption and sedimentation of flocs. So, when the sludge reflux ratios are 50 and 67%, the SS removal efficiency could reach a higher level. In addition, compared with the data in Fig. 3, the SS removal rate decreases, instead of increasing, with the increase of sludge reflux ratio (>67%). The results suggest that when sludge reflux ratio exceeds a certain value, the content of suspended substances in water increases, thusly, imposing a negative effect on SS treatment.

The results of TP removal under different sludge reflux ratios are shown in Fig. 4.

Phosphorus in wastewater is primarily removed by applying the coagulation–sedimentation process, so it is liable to the impact of flocculant enriched in the return sludge. In the range of tested sludge reflux ratios, the treatment effect of TP generally increases with the test time. TP values tend to be stable gradually after running of 80 min, so it is suggested that the treatment effect of TP has reached a stable state. As we can see in Fig. 4, when the sludge reflux ratios are 0% and 33%, the highest TP removal rates only reach 48.73 and 63.33%, respectively. The values of TP in effluent water are 1.82 and 0.92 mg/L, and water quality is obviously poorer than that under other sludge reflux ratios. When the sludge reflux ratio is higher than or equal to 83%, the TP removal rate decreases instead of increasing. When the sludge reflux ratios

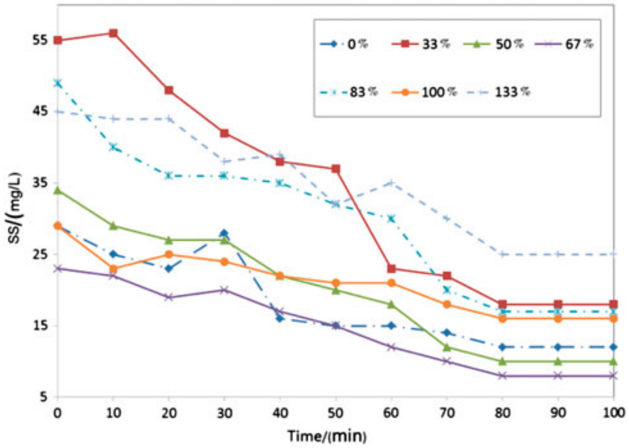

Fig. 3. Results of SS removal under different sludge reflux ratios.

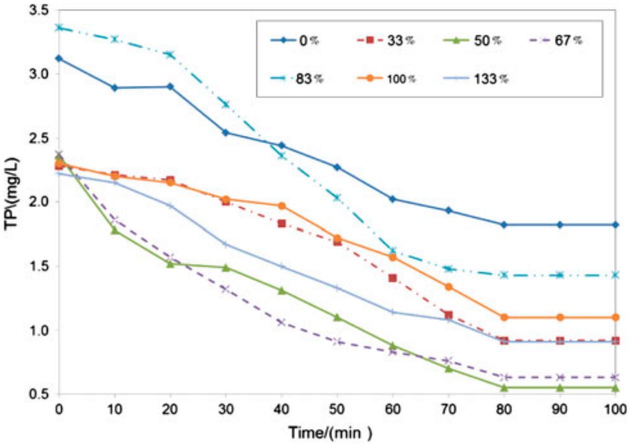

Fig. 4. Results of TP removal under different sludge reflux ratios.

are 50 and 67%, the TP removal rates are similar and reach 85.01 and 76.40%, and the values of TP in effluent water are 0.55 and 0.63 mg/L, respectively. These TP removal rates are higher than those under other sludge reflux ratios, indicating that TP can be effectively removed by the high-efficiency sedimentation process in a stable way when the sludge reflux ratios are within an appropriate range.

The results of COD removal in effluent water under different sludge reflux ratios are shown in Fig. 5.

Fig. 5 shows that COD can be removed to some extent under different tested sludge reflux ratios and COD values tend gradually to be stable after running of 80 min. After comprehensive analysis on seven kinds of working conditions for COD removal, we have found that all COD removal rates by the return sludge process are relatively high. As these results shown, when the sludge reflux ratio is 50%, the value of COD in effluent water is 40.11 mg/L and the COD removal rate reaches 75.10%, meeting Grade 1A of *Discharge standard of pollutants for municipal wastewater treatment plant* (GB18918-2002). Effluent water quality under this sludge reflux ratio is significantly higher than that under other sludge reflux ratios.

3.2. *The impact of different sludge reflux ratios on the sludge sedimentation performance*

The results of SC, SV and SVI values of sludge under different sludge reflux ratios are shown in Figs. 6-8, respectively.

SVI, which is equal to the ratio of SV to MLSS, mainly reflects the cohesion and sedimentation performances of sludge. As shown in Figs. 6-8, when the sludge reflux ratios are 50 and 67%, SVI values are less than those under other sludge reflux ratios, indicating that the sludge in the system can be settled well under the two working conditions.

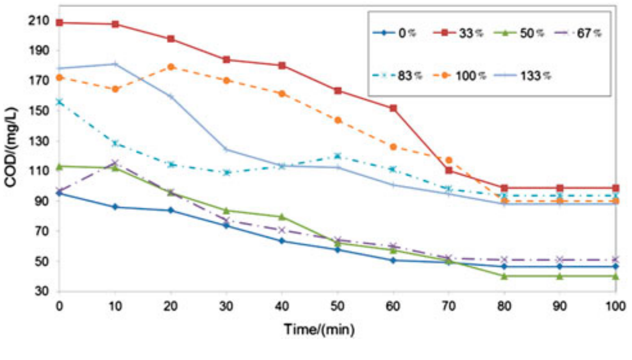

Fig. 5. Results of COD removal in effluent water under different sludge reflux ratios.

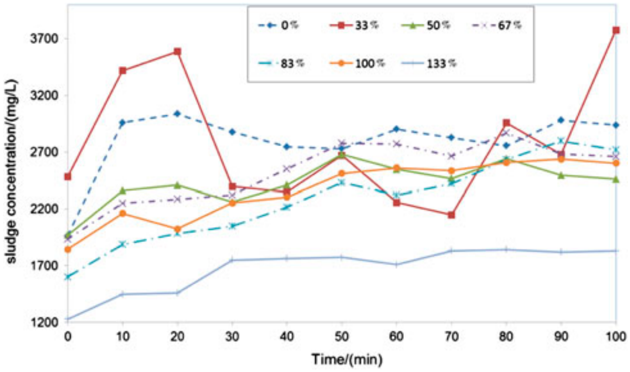

Fig. 6. SC under different sludge reflux ratios.

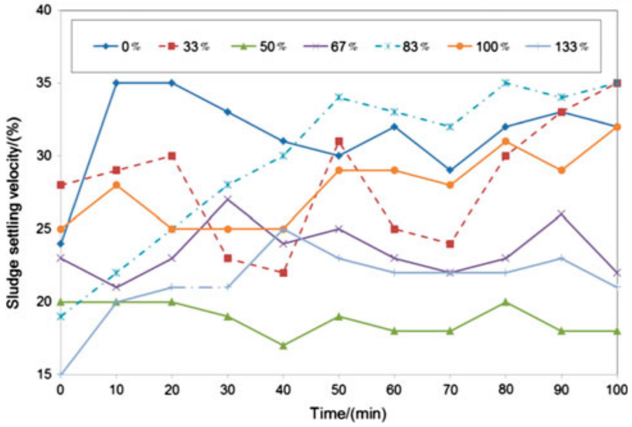

Fig. 7. Sludge SV value under different sludge reflux ratios.

In conclusion, when the sludge reflux ratios are 50 and 67%, the treatment with the pilot device can achieve a better effect. The SS removal rates are 73.19 and 65.96%, the TP removal rates are 85.01 and 76.74% and the COD removal rates are 75.10 and 71.07%, respectively. Moreover, the SVI value under this condition is less than that under other working conditions, so the sedimentation performance of sludge in the system is better. After comprehensive consideration of treatment efficiency of the device and economic benefits, the optimal sludge reflux ratio is confirmed to be 50%.

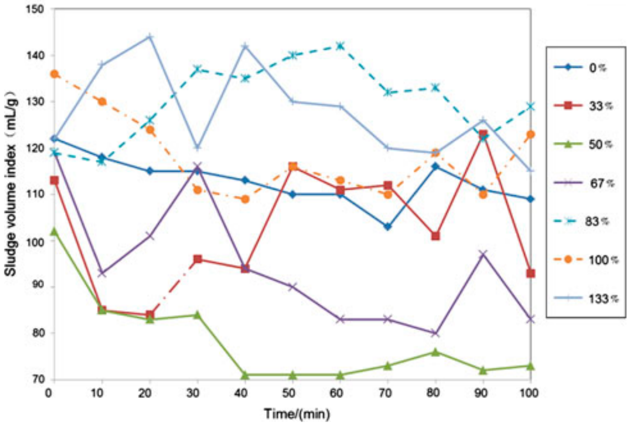

Fig. 8. Sludge SVI value under different sludge reflux ratios.

3.3. Analysis of optimal working condition of the pilot device

The optimal working condition of the pilot device is determined through the above tests. The parameters of optimal working condition are as follows: the concentration of $FeCl_3$ used as the coagulant is 10.26 mg/L (measured in Fe^{3+}) and the concentration of PAM used as the coagulant aid is 0.80 mg/L. The operational parameters of the mixing equipment are as follows: stirring speeds of the mixing tank and the

Table 4
Measurement of relevant water quality indicators under optimal working condition

Indicator	pH value	TP (mg/L)	UV254	TN (mg/L)	Ammonia nitrogen (mg/L)	COD (mg/L)	DCOD (mg/L)
Raw water	7.92	2.63	0.301	44.85	27.57	248.1	221.62
Effluent water	7.55	0.48	0.249	21.14	16.23	49.54	44.58
Removal rate (%)	–	81.75	–	52.87	41.83	80.03	79.88

Table 5
Values of SS penetrating filter membrane with different sizes under optimal working condition

SS value (mg/L)	Membrane pore size (μm)							Total
	≥50	12–50	8–12	5–8	3–5	1–3	≥1	
Raw water	15	14	4	2	3	2	3	43
Effluent water	0	0	1	1	2	2	3	9
Removal rate (%)	100	100	75	50	33.33	0	0	79.07

reaction tank are 120 and 80 rpm, respectively. The flow of influent water to the pilot device is 120 L/h and the return sludge volume is 60 L/h. Sludge is discharged intermittently. Water samples are taken from the device after 35 min of pre-flocculation and 120 min of device running. Indicators for measurement and evaluation are pH value, SS, COD, DCOD, TP, UV254, TN, ammonia nitrogen, etc.

Water samples are taken, after that the pilot device has run for 115 min under the optimal working condition to measure the relevant indicators of water quality (Table 4), and the values of SS penetrating filter membrane with different sizes shall be measured (Table 5).

It can be seen from Table 4 that TP, COD and DCOD can be removed effectively by treatment with the pilot device after that the high-efficiency sedimentation tank has run for 115 min under the optimal working condition. The effluent water quality is up to *Discharge standard of pollutants for municipal wastewater treatment plant* (GB18918-2002) (Grade 1A), but the removal effects of TN and ammonia nitrogen are not obvious.

Table 5 shows that after the treatment by the high-efficiency sedimentation process, large particles with sizes of 12 μm or above in the wastewater could be fully eliminated, the particles with sizes ranging from 3 to 12 μm could be partially eliminated and it is impossible to remove the particles with sizes of 3 μm or below. The reason is that the probability of collision between the small-sized particles is low and the effective aggregation and sedimentation are hard to be achieved. Therefore, the particles are hard to be removed. For large-sized particles, the concentration of particles in water is higher and the probability of collision between them is relatively high, so the effective aggregation and sediment can be achieved. Larger floc produced can be settled well together with the sludge, so the removal effect is significant.

4. Conclusions

The following conclusions are drawn from the experimental study:

(1) High-efficiency sedimentation technology shows a good effect on SS, TP and COD treatment in wastewater, and the removal rate could reach around 80%, with stable removal effect. However, the TN removal effect is not obvious.
(2) Return sludge has a great impact on the operation effect of the sedimentation tank, and the optimal sludge reflux ratio is confirmed to be 50% through tests.
(3) After treatment in the high-efficiency sedimentation tank, the particles with sizes of 12 μm or above in the wastewater could be fully eliminated, the particles with sizes ranging from 3 to 12 μm could be partially eliminated and the particles with sizes of 3 μm or below cannot be removed.
(4) The water quality of secondary effluent from municipal wastewater treatment plant can basically meet the requirements of *The Reuse of Urban Recycling Water–Water Quality Standard for Scenic Environment*

Use (GB/T 18921-2002) after sedimentation treatment in high-efficiency sedimentation tank.

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