Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28014

246 (2022) 146–155
January

Application of magnetic coagulation for the advanced treatment of ethylene glycol wastewater

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Received 4 June 2021; Accepted 10 November 2021

ABSTRACT

Due to technological innovation, the influent for advanced treatment has increased, while the capacity of mechanical clarifiers is limited, which has led to a decrease in the effective removal of pollutants, so this paper explores the feasibility of using magnetic coagulation instead of conventional coagulation. The effect of each factor on coagulation is studied, and then the parameters are optimized by an orthogonal test. The optimum conditions are as follows: the doses of poly aluminium chloride and polyacrylamide are 40 and 1 mg L^{-1}, respectively, the initial pH is 7.0, and the dose of magnetic powder (200 mesh) is 80 mg L^{-1}. The average recovery of magnetic powder is 96.99%, and the properties of the recovered magnetic powder remain stable. Compared with values obtained in conventional coagulation, the removal rates of the chemical oxygen demand, turbidity and SiO_2 increase by 7.0%, 6.6% and 5.1%, respectively, and reagent cost decreases by 26.6%. The sedimentation time of conventional coagulation is approximately 30 min, while that of magnetic coagulation is approximately 2 min. The average sedimentation rate of magnetic coagulation is 14 times faster than that of conventional coagulation. Therefore, it is feasible to use magnetic coagulation.

Keywords: Coagulation; Magnetic powder; Poly aluminium chloride; Polyacrylamide; Sedimentation rate

1. Introduction

A coal chemical industry-limited company produces ethylene glycol with coal as the raw material, and many types of wastewater are produced by this project, which makes treatment difficult. Sewage stations use diverse pre-treatments and a combination of multiple processes to treat wastewater, the process flow diagram is as shown in Fig. 1.

At present, the production process of the company technological innovation, the use of water in the company area increased, the use of renovated water as circulating water is necessary. The demineralized water station and the clean circulating cooling water system require high quality of the supplementary water, the raw water is still used as the supplementary water, therefore, the sewage treatment reclaimed water from a certain county is used in the turbid circulating cooling water system, the amount of turbid circulating sewage discharge is increased from 209 to 290 m^3 h^{-1}, the amount of water and pollutants entering the sewage treatment station are increased, and the capacity of the mechanical stirring clarifier is limited and the residence time is short, the removal rate of suspended solids (SS) and chemical oxygen demand (COD) is low [1]. Due to the existence of ultra-fine fly ash in the integrated wastewater of coal chemical industry, the content of soluble SiO_2 is high, and the subsequent treatment unit has a low removal rate of soluble SiO_2, the

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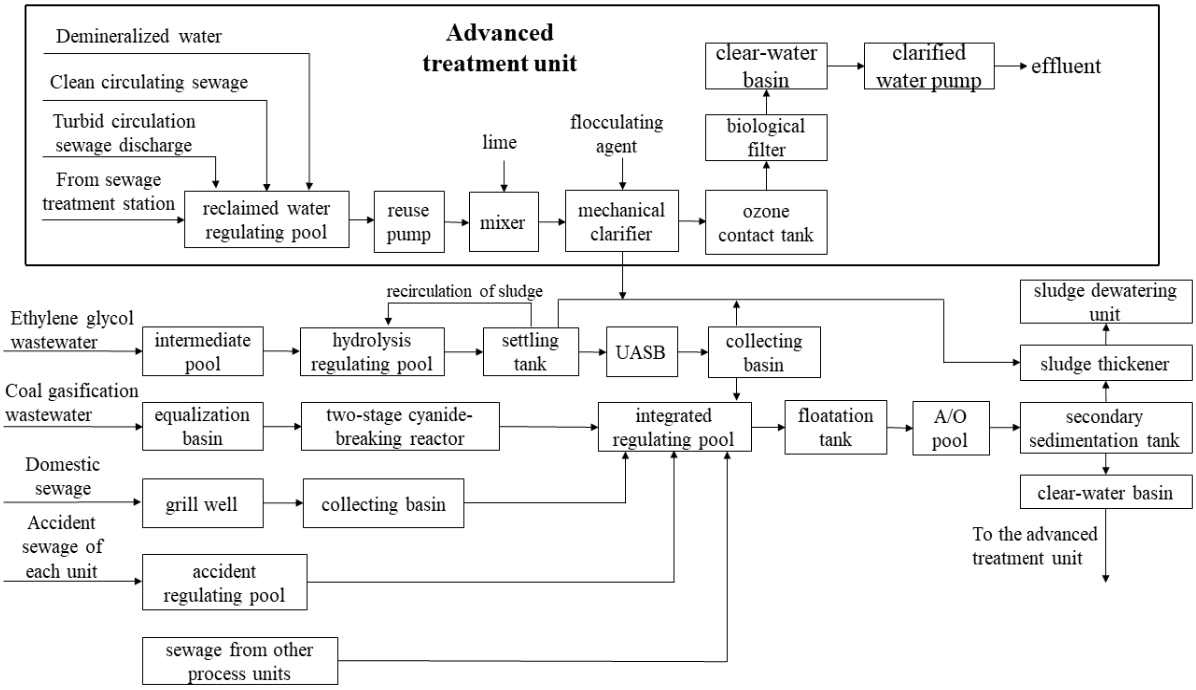

Fig. 1. Flow chart of wastewater treatment station of the coal chemical enterprise.

quality of effluent from the wastewater treatment station is muddy, and the contents of suspended matter and chroma are high, difficult to meet emissions standards, and the subsequent processing unit has a certain impact.

In view of the problem existing in sewage stations, based on not adding additional civil facilities and facilitating the upgrading of the existing process, to improve the removal rates of SS, COD and soluble SiO_2, magnetic coagulation is adopted to treat wastewater instead of conventional coagulation. Magnetic coagulation technology adds magnetic seeds in the coagulation process. Magnetic seeds, similar to fine suspended particles, act as nuclei in the coagulation process, increasing the effective collision rate of particles, so the addition of magnetic particles is beneficial to floc aggregation and coagulation performance. Colloidal particles and magnetic powder particles aggregate under the action of Johannes van der Waals forces. Then, under the action of adsorption and bridging of flocculants, the flocs are further agglutinated and enlarged, and the flocculants, magnetic seeds and pollutants are combined into a whole to form magnetic complexes, which improves the pollutant removal effect. Then, solid–liquid separation is realized by large specific gravity and rapid sedimentation, and the magnetic seeds can be recycled by a subsequent magnetic separation device, thus reducing materials cost [2–5].

The advantages of magnetic coagulation technology, such as simple operation, large treatment capacity, high treatment efficiency, low energy consumption, low sludge yield and significant reduction of follow-up load, have attracted much attention, it has been applied to all aspects of water treatment [6–14]. Lv et al. [15] discussed magnetic coagulation to treat surface water, and the addition of magnetic particles accelerates the sedimentation rate, while the turbidity removal rate increases from 89.75% to 96.80%, and the sedimentation time is shortened from 30 to 2 min. Chin et al. [16] used magnetic coagulation to remove SiO_2 from chemical mechanical polishing wastewaters, and the wastewater turbidity is reduced from 110 to 7 NTU. Tang et al. [17] discussed the magnetic coagulation to remove oil-containing micro-polluted wastewater, the results showed that the removal rate of oil exceeds 90% and the reaction time was shortened significantly. Chen et al. [18] used magnetic coagulation-sequencing batch membrane Bioreactor to treat swine wastewater, the removal rates of COD, TN and TP were over 90%, and the hydraulic retention time was shortened from 5 to 4.3 d.

This paper explores the possibility of using magnetic coagulation to replace conventional coagulation. First, the effects of various factors, such as magnetic powder dose, coagulant dosage, flocculant dosage, initial pH value, and dose sequence, on the magnetic coagulation effect are investigated, and then experimental parameters are optimized by performing orthogonal experiments to maximize the magnetic coagulation performance. Furthermore, the recovery rate and reuse feasibility of the magnetic powder are studied. Finally, by comparing the differences in treatment capacity and cost between conventional coagulation and magnetic coagulation, this approach provides a practical method for the efficient and advanced treatment of coal chemical wastewater.

2. Materials and methods

2.1. Materials

The test wastewater was taken from the regulating tank of the advanced treatment stage of the sewage station. Table 1 lists the statistical data for 7 parameters; the first

Table 1
Statistical data of water quality parameters

Parameter	Minimum	Maximum
Temperature, °C	30	33
pH	8.2	8.5
COD, mg L^{-1}	55	65
Turbidity, NTU	23	27
SS, mg L^{-1}	65	90
Soluble SiO_2, mg L^{-1}	35.8	38.0
NH_3–N, mg L^{-1}	25	32

and second columns list the parameters and corresponding units, and the third and fourth columns show the statistical data for each parameter.

The main chemicals are shown below. Hydrochloric acid was purchased from Luoyang Chemical Reagent Factory (Luoyang, China). Poly aluminium chloride (PAC) and polyacrylamide (PAM) were purchased from Tianjin Dingshengxin Chemical Co., (Tianjin, China), the physicochemical properties of PAC and PAM are shown in Table 2. Magnetic powder was purchased from Hebei Senyuan Metal Material Co., (Hebei, China). Oxalic acid and sodium hydroxide were purchased from Tianjin Kemio Chemical Reagent Co., (Tianjin, China). Ammonium iron (II) sulfate was purchased from Shantou Xilong Chemical Co., (Shantou, China). Except for the magnetic powder, all reagents used were analytically pure.

2.2. Jar test

Coagulation experiments were performed using a TJ-6 program-controlled jar test apparatus (Wuhan Hengling Technology Co. Ltd., China) at room temperature. One litre of wastewater was transferred into a beaker. First, magnetic powder was added and stirred quickly (120 rpm) for 1 min. Then, PAC was added. Second, PAM was added and stirred at medium speed (40 rpm) for 10 min, followed by a 15 min settling time. The supernatant sample was extracted from the beaker 2 cm below the water surface for analysis of water characteristics. For the traditional coagulation test, no magnetic powder was added, but other steps were the same as those in the magnetic coagulation test. The average removal rate was calculated from three parallel experiments and optimized by orthogonal design.

2.3. Magnetic powder recycling and utilization

To investigate the influence of the magnetic powder recovery rate and the number of uses on the pollutant removal effect, the used magnetic powder was recovered. First, the treated wastewater was removed from the supernatant, and then the magnetic floc was transferred to a 500 mL beaker and stirred rapidly (200 rpm) for 5 min. Second, the magnetic floc was placed at the bottom of the beaker, and adsorption proceeded for 3 min. After the magnetic powder was cleaned, the process was repeated until the supernatant was clarified. Finally, the samples were dried in a constant-temperature oven at 50°C.

2.4. Analytical methods

The pH and temperature were measured by a pH meter (S220-K-CN, China) and thermometer (S220-K-CN, China). The turbidity was measured by a turbidimeter (2100 N, Hach, USA). COD was measured by digest instrument (5B-1B (V8, China)). Soluble SiO_2 was measured by a spectrophotometer (VIS-723N, China). The magnetic powder weight was measured by an electronic balance (PL4002, China).

All analyses were conducted in three groups of parallel tests, the results of which were expressed as the means. The calculations were performed with the statistical program SPSS 20.0 (SPSS Inc., Chicago, USA) and Excel 2013 (Microsoft Office Standard). Analysis of variance (ANOVA) was used to determine whether different influencing factors caused significant differences in pollutant removal rates, and the difference was considered significant if $p < 0.05$.

3. Results and discussion

3.1. Optimization of magnetic coagulation parameters

3.1.1. Effect of magnetic powder dosage

Magnetic powder not only affects the removal effect but also affects economic benefits; therefore, the effect of magnetic powder was investigated. The results are shown in Fig. 2.

The results showed that the removal rates of COD, turbidity and soluble SiO_2 increased with increasing magnetic powder and that the dose had a significant effect on pollutants ($p < 0.05$). When the dose was increased from 0 to 80 mg L^{-1}, the removal rate increased quickly. When the dose was 80 mg L^{-1}, the removal rates of COD, turbidity and

Table 2
The physicochemical properties of PAC and PAM

Index	PAC	PAM
Chemical composition	$[Al_2(OH)_nCl_{6-n}]m$	$(C_3H_5NO)n$
Color	Yellow	White
Water solubility	Easily soluble in water	Easily soluble in water
Insoluble (%)	≤1.5	≤2
Material type	inorganic polymers	Organic polymer
Mechanism of action	Charge neutrality compression diffusion layer	Adsorption bridging charge neutrality

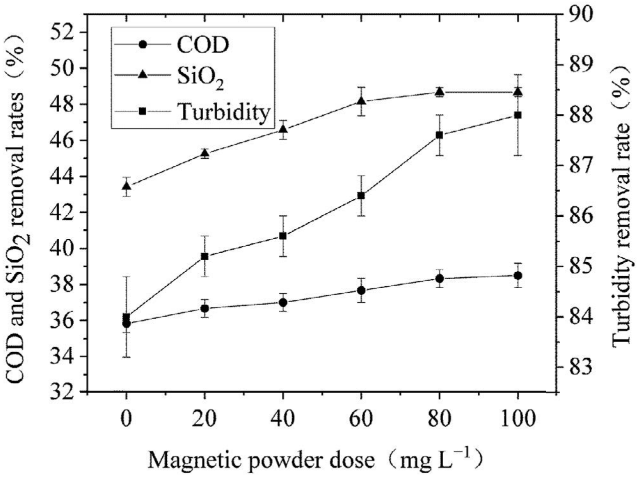

Fig. 2. Effect of magnetic powder dose on pollutant removal (200 mesh magnetic powder, 40 mg L⁻¹ PAC, 1.0 mg L⁻¹ PAM, initial pH of 8.2).

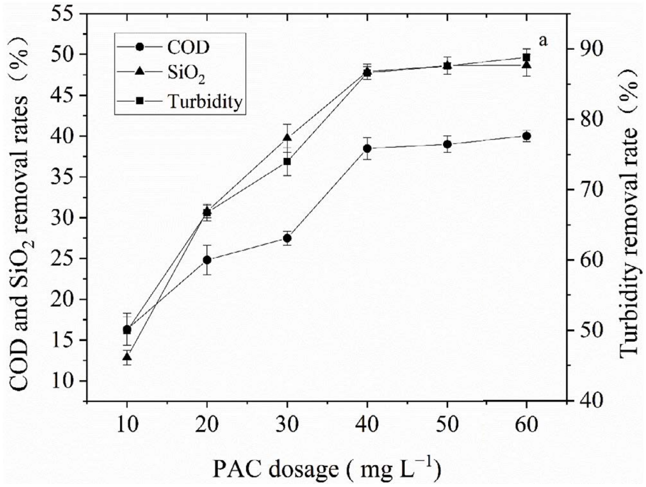

Fig. 3. Effect of coagulant dose on pollutant removal (80 mg L⁻¹ 200 mesh magnetic powder, 1.0 mg L⁻¹ PAM, initial pH of 8.2).

soluble SiO_2 reached 38.3%, 87.6% and 48.7%, respectively, and it had better removal efficiency. Increasing the dose of magnetic powder within a certain range is equivalent to increasing the crystal nucleus, and magnetic powder also increases the particle collision probability and further promotes the formation of flocs. And magnetic powder has a large specific surface area, it can undergo physical and chemical adsorption [19], which may enhance the adsorption of pollutants [20], the magnetic powder is adsorbed in the flocs to form a magnetic copolymer, which has a more compact structure and contains more contaminants, thus improving the removal of contaminants [21,22]. With an increase in the dose to 100 mg L^{-1}, the removal rates exhibited little change and even tended to be stable. This result occurred because magnetic powder reached adsorption saturation on the surface of the flocs, the floc magnetic susceptibility remained basically unchanged [23], and the excessive magnetic powder particles collided with each other, reducing the flocculation effect and causing a waste of resources. Therefore, the optimal dose of magnetic powder is 80 mg L^{-1}.

3.1.2. Effect of the dosage of coagulant and flocculant

After determining the optimal dose of magnetic powder, the effects of coagulant and flocculant were further studied. The results are shown in Figs. 3 and 4.

The results showed that the removal rates of COD, turbidity and soluble SiO_2 increased with increasing PAC and PAM dose and that dose had a significant effect on the removal rate of pollutants ($p < 0.05$).

When the dose of PAC was 10–40 mg L^{-1}, the contaminant removal rate increased quickly. This is because the Zi ζ potential is negative when achieving electrical neutralization, positive ions from the hydrolysis of aluminium chlorohydrate concentrate around negatively charged colloidal particles and magnetic particles, then the electrostatic magnetic force disappears, colloidal particles and magnetic particles aggregate under the action of Johannes van der Waals forces, and contaminants can be removed [24]. Addition of PAC increased the collision frequency and aggregation among magnetic powder and suspended solid particles, it's also good for pollutants. When the dose of PAC was 50 mg L^{-1}, compared with 40 mg L^{-1}, only 2.8%, 4% and 3.4% were increased. This result was due to the increase in counter-charged polymerized ions when the dose of coagulant was too high, which changed the surface charge properties of the gel core, making the gel re-stabilize and reducing the coagulation effect [25,26]; an excessive dose of coagulant may easily lead to an increase in the volume of sludge to be dewatered, and the coagulant may remain in the water and be difficult to remove [27]. When the dose of PAC was 40 mg L^{-1}, the turbidity of the effluent was less than 5.0 NTU, the COD was less than 40.0 mg L^{-1}, the soluble SiO_2 content was approximately 21.2 mg L^{-1}, and the concentration of soluble SiO_2 met the requirement for reclaimed water systems (≤25.0 mg L^{-1}). Therefore, the optimum dose of coagulant is 40 mg L^{-1}.

When the dose of PAM was 0.5 mg L^{-1}, there were some particles that had not formed flocs, and the removal efficiency of pollutants was low [28]. In the range of 0.5–1.0 mg L^{-1}, the removal efficiency of pollutants increased rapidly; however, when the dose of PAM was more than 1.0 mg L^{-1}, the removal rate of pollutants, especially COD and soluble SiO_2, was limited. This may be due to increased binding of polyacrylamide to magnetic particles, which may lead to the formation of denser magnetic flocs [29]; the resulting compact and stable flocs will help to improve the removal efficiency and settling rate [30]. However, too much dosing will cause the flocs to form a package, the repulsion between the polymers hinders connection between the flocs, and it will decrease the settling rate. Therefore, the removal rate showed a tendency to increase quickly and then slowly with an increase in the dose of PAM [31]. Considering the economic factors and removal effect, the optimum dose of PAM is 1.0 mg L^{-1}.

3.1.3. Effect of initial pH

The initial pH value is another factor affecting the treatment effect, so the removal effect was investigated

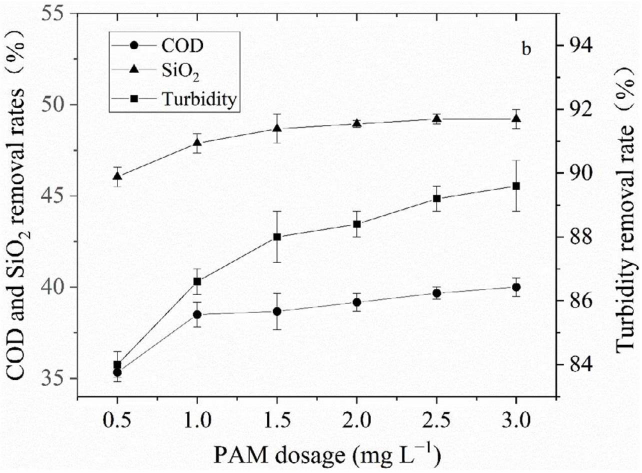

Fig. 4. Effect of flocculant dose on pollutant removal (80 mg L^{-1} 200 mesh magnetic powder, 40 mg L^{-1} PAC, initial pH of 8.2).

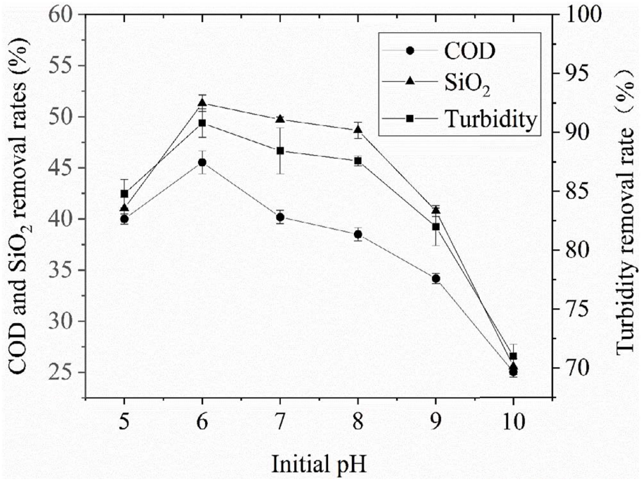

Fig. 5. Effect of pH on pollutant removal (80 mg L^{-1} 200 mesh magnetic powder, 40 mg L^{-1} PAC, 1.0 mg L^{-1} PAM).

by adjusting the initial pH value. The results are shown in Fig. 5.

The results showed that the removal rates of COD, turbidity and soluble SiO_2 first increased and then decreased with the change in pH and that pH had a significant effect on the removal of pollutants ($p < 0.05$). When the initial pH was 6.0, the removal rates of COD, turbidity and soluble SiO_2 reached their highest levels of 45.6%, 90.8% and 51.3%, respectively. When the initial pH value decreased or increased, the pollutant removal rate decreased. When the pH value was close to 8.0, the removal rates of COD, turbidity and soluble SiO_2 were 38.5%, 87.6% and 48.7%, respectively, as the pH value continued to increase, the removal rate began to significantly decrease. In the process of magnetic coagulation, pH has a great influence on the pollutant removal performance, mainly because pH has a significant influence on the magnetic powder adsorption performance [32]. The pH will affect the zeta potential of the magnetic seeds, which will affect the magnetic separation efficiency [33]. With increasing or decreasing pH, the surface load of the magnetic seeds will increase, resulting in an increase in the electrostatic repulsion force, which is not conducive to the removal of contaminants [34]. Therefore, when the initial pH value was in the range of 6.0–8.0, magnetic coagulation had a better treatment effect, and the best effect was obtained at pH 6.0.

3.1.4. Effect of dosing sequence

Since the dosing sequence will affect the removal of pollutants, this factor was also studied. Tests were carried out by adding reagents in the order of magnetic powder + PAC + PAM, PAC + magnetic powder + PAM, and PAC + PAM + magnetic powder. The pollutant indexes were determined after natural sedimentation for 15 min.

The results showed that the pollutant removal effect obtained when adding magnetic powder, then adding PAC, and finally adding PAM was the best. Under these conditions, the removal rates of COD, turbidity and soluble SiO_2 were 38.5%, 87.6% and 48.1%, respectively. However, the removal rates of COD, turbidity and SiO_2 decreased by 1.1%, 1.9% and 2.9%, respectively, when the dose sequence was "PAC + magnetic powder + PAM", and the removal rates of COD, turbidity and SiO_2 decreased by 1.7%, 2.5% and 3.9%, respectively, when the dose sequence was "PAC + PAM + magnetic powder". Therefore, "magnetic powder + PAC + PAM" is the best dose sequence.

The dosing sequence influences the removal rate. The main reason is that magnetic powder can be evenly distributed by adding it first. Suspensions and destabilized colloidal particles frequently collide with magnetic particles, are adsorbed on the surface of the magnetic particles under suitable turbulent flow conditions and have a certain magnetism, which is beneficial to the subsequent flocculation of flocs. Adding PAC next will make the pollutants easier to collect. Finally, with the help of PAM, complex flocs with higher density are synthesized, which more easily precipitate [35].

3.1.5. Orthogonal optimization test

To determine the best treatment conditions of magnetic coagulation, an orthogonal test was used to optimize the treatment conditions. The magnetic powder dose, PAC dose, PAM dose and initial pH were selected as four factors, and each factor was assigned three levels, resulting in a four-factor three-level orthogonal test. The orthogonal test scheme and results are shown in Table 3.

Through range and multi-index comprehensive analysis, it was found that the order of influence on magnetic coagulation was PAC dose > initial pH value > PAM dose > magnetic powder dose. The PAC dose had a great influence on the COD and turbidity removal rates, and the removal effect was best when the PAC dose was 40 mg L^{-1}. The initial pH value had a great influence on the removal rates of soluble SiO_2 and COD, and the removal effect was best when the pH was 7. The dose of PAM had a great influence on the removal rate of turbidity but had little influence on the removal rates of COD and soluble SiO_2. The best turbidity removal rate was obtained at a PAM dose of 1.0 mg L^{-1}. Compared with the effects of other factors, the dose of magnetic powder had little effect on the removal rates. Considering the above research results and cost considerations, the dose of magnetic powder was 80 mg L^{-1}.

Therefore, the optimal conditions were a PAC dose of 40 mg L^{-1}, an initial pH value of 7.0, a PAM dose of 1.0 mg L^{-1}, and a magnetic powder dose of 80 mg L^{-1}.

3.2. Recovery and reuse of magnetic powder

The recovery rate of magnetic powder and the effect of use time on the removal efficiency were investigated. The used magnetic powder was recovered, the recovery rate of magnetic powder was calculated, and the recovered magnetic powder was tested in parallel experiments. In the three experiments, the doses of magnetic powder added were 0.163, 0.165 and 0.170 g, the doses of magnetic powder recovered was 0.159, 0.158, and 0.166 g, respectively, the recovery rate was 97.55%, 95.76% and 97.65%.

The average recovery rate of magnetic powder was 96.99%, but there was also a 3.01% loss. The first reason was that in the recovery process, although the magnet block adsorption, but the magnetic powder did not completely precipitate down, with the upper liquid loss; the second reason was that the dosage of magnetic powder added in the test process was less, and there were some errors in the drying and weighing process.

The recycled magnetic powder was reused in the magnetic coagulation test to investigate the effect of the number of times of use on the removal of pollutants. After repeated use of magnetic powder for 1–5 times, the contamination was determined, as it turns out, the removal rates of COD and SiO_2 fluctuated by 0.6%, and the turbidity removal rate fluctuated by 0.7%. The properties of the magnetic powder remained stable after repeated use, so the magnetic powder could be reused many times.

3.3. Economic feasibility analysis of magnetic coagulation technology

3.3.1. Comparison of the removal effects of magnetic coagulation and conventional coagulation

A conventional coagulation test was carried out under the same conditions as above except for magnetic powder to understand advantages of magnetic coagulation, and the difference in removal rate was determined. The results are shown in Figs. 6 and 7.

As shown in Figs. 6 and 7, the removal of COD, turbidity and soluble SiO_2 showed similar trends, and the removal rates increased with increasing PAC and PAM dosages. At the same dosages of PAC (40 mg L^{-1}) and PAM (1 mg L^{-1}), the removal rates of COD, turbidity and SiO_2 by magnetic coagulation were 7.0%, 6.6% and 5.1% higher, respectively, than those by conventional coagulation. At the appropriate PAC dosage (40 mg L^{-1}) in the magnetic coagulation, further analysis showed that removal rates of COD, turbidity and soluble SiO_2 reached 38.5%, 86.6% and 47.8%, respectively, however, more than 60 mg L^{-1} PAC was added to achieve this effect in the conventional coagulation, so the dosage of PAC was reduced by 33%. Wang et al. used magnetic coagulation to treat slightly polluted surface water, mainly removing organic matter and turbidity, under the best conditions, the dosage of magnetic coagulation PAC was 25% less than that of conventional coagulation [36]. In addition, the dosage of PAM was 1 mg L^{-1}, under which condition the removal rates of COD, turbidity and soluble SiO_2 were 38.5%, 87.6% and 47.9%, respectively, however, the same removal effect could not be achieved in conventional coagulation even when the dosage of PAM was increased to 3 mg L^{-1}. Wang used magnetic coagulation to treat tail water of city Sewage Treatment. The optimum conditions were as follows: PAC dosage 50 mg L^{-1}, magnetic powder dosage 500 mg L^{-1}, optimum sedimentation time 6 min, optimum dosage was higher, this test has great advantage in the application of medicament [37].

These results were obtained because magnetic powder has a large specific surface area and surface activity. When magnetic powder adsorbs the amount of organic matter, its surface activity is reduced, and the powder thus reaches a stable state and forms a mass precipitate during continuous adsorption and magnetic polymerization, it can be well combined with PAC and PAM to form composite magnetic flocculants, which makes mutual attraction between flocs increase, thus increasing collision probability of colloidal particles [38]. Therefore, under the same dosages of coagulant and flocculant, the removal rates by magnetic coagulation are higher than those by conventional coagulation.

The economic costs of magnetic coagulation and conventional coagulation in treating coal chemical wastewater were compared and analysed on the premise of obtaining the same treatment effect. The results are shown in Table 4. The total reagent cost of magnetic coagulation was 0.11 yuan m^{-3}, while conventional coagulation was 0.15 yuan m^{-3}, and the reagent consumption in the former was 26.6% lower than that of the latter. Moreover, the magnetic powder is recycled after separation and recovery, and the loss is low, therefore, the magnetic coagulation treatment has cost advantages.

3.3.2. Performance analysis of magnetic coagulation sedimentation

The sedimentation time of magnetic coagulation and conventional coagulation under suitable treatment conditions were compared and analysed. The results are shown in Fig. 8.

As shown in Fig. 8, compared with conventional coagulation, the sedimentation performance of magnetic coagulation was significantly improved. Conventional coagulation sedimentation was stable in approximately 30 min, and the average sedimentation rate was 0.27 cm/min; magnetic coagulation sedimentation was stable in approximately 2 min, and the average sedimentation rate was 3.85 cm/min, 14 times faster than that of conventional coagulation. Zhang et al. used magnetic coagulation to treat coal mine water, the settling time is about 2 min [39], which is basically consistent with our experimental results, and magnetic coagulation significantly increased the sedimentation rate.

These results mainly occurred because the addition of magnetic particles increases the probability of collision between particles, which is favourable for the formation of magnetic flocs and the removal of contaminants [40]. The magnetic powder has a greater density, and the density of magnetic flocculation also increases significantly, making it easier to settle and separate [41]. In the process of magnetic coagulation, the removal efficiency of pollutants is better because of the multiple effects of magnetic seeds (suspended particles, adsorbents and coagulants), and

Table 3
Factor level table and results of the orthogonal test

Test number	PAC dose ($mg\ L^{-1}$)	PAM dose ($mg\ L^{-1}$)	pH	Magnetic powder dose ($mg\ L^{-1}$)	COD removal rate (%)	Turbidity removal rate (%)	SiO_2 removal rate (%)
1	30	0.5	6	60	35.8	82.63	44.30
2	30	1.0	7	80	34.25	83.50	46.32
3	30	1.5	8	100	37.43	82.74	42.50
4	40	0.5	7	100	35.86	85.95	45.36
5	40	1.0	8	60	38.65	86.43	45.05
6	40	1.5	6	80	39.50	87.55	48.25
7	50	0.5	8	80	40.26	86.05	44.23
8	50	1.0	6	100	41.30	88.32	51.05
9	50	1.5	7	60	39.53	87.25	49.20

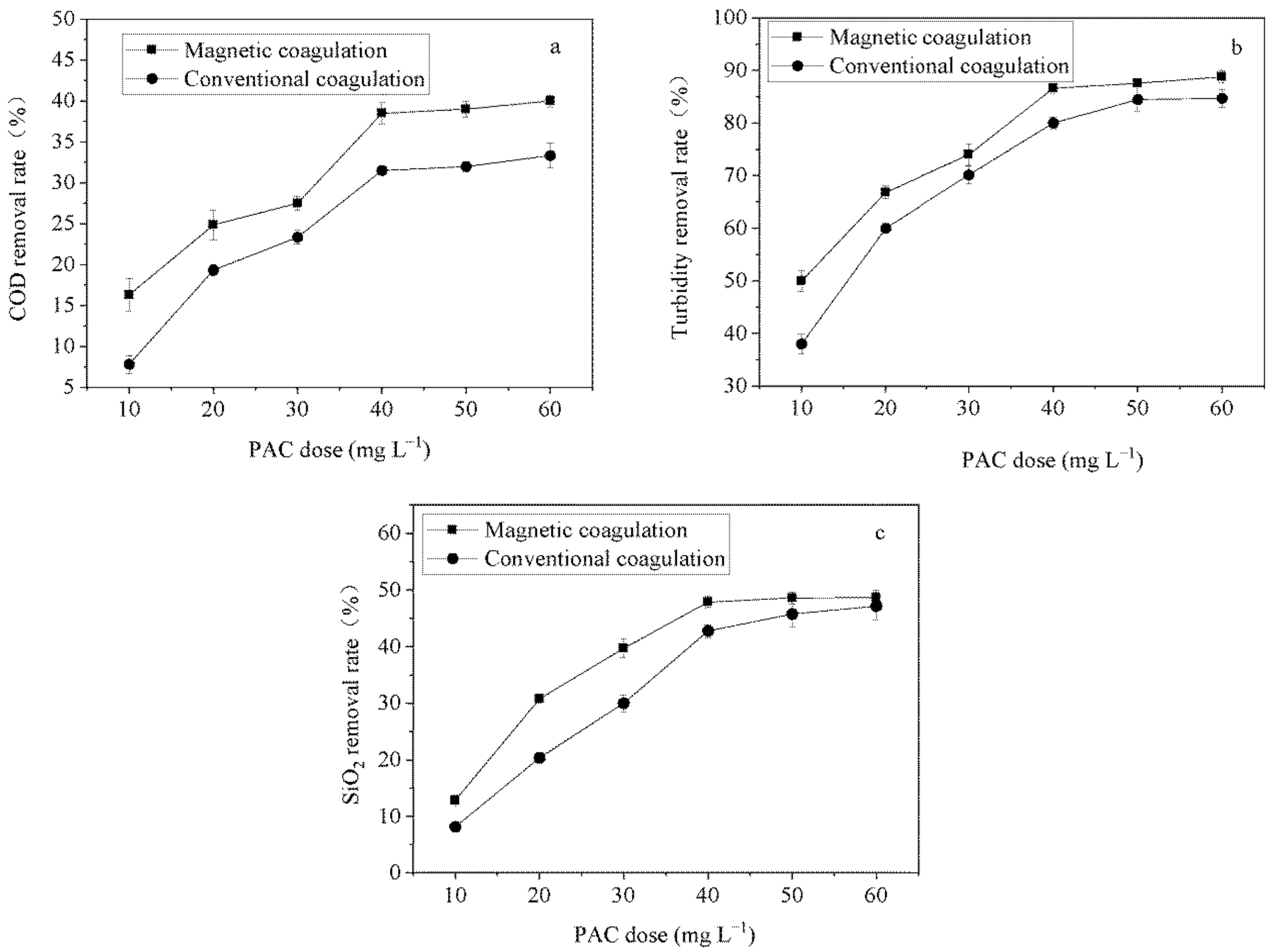

Fig. 6. Influence of PAC on magnetic coagulation and conventional coagulation (200 mesh magnetic powder, 1.0 mg L^{-1} PAM, pH 7).

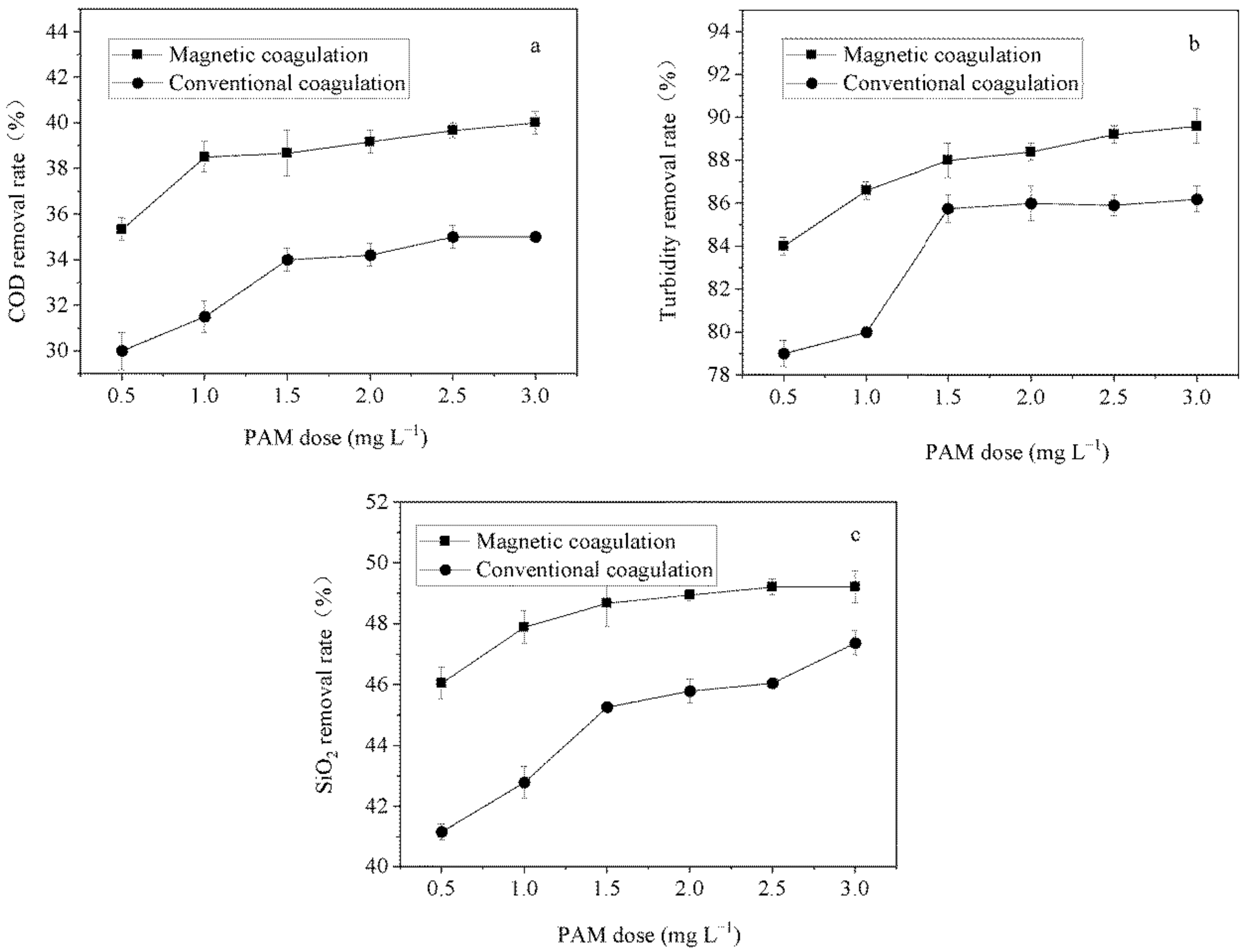

Fig. 7. Influence of PAM on magnetic coagulation and conventional coagulation (200 mesh magnetic powder, 40 mg L^{-1} PAC, pH 7).

Table 4
Comparison of consumption and cost between magnetic coagulation and conventional coagulation

Contrast item	Conventional coagulation	Magnetic coagulation
PAC (2,000 yuan t^{-1})	60 mg L^{-1}	40 mg L^{-1}
PAM (20,000 yuan t^{-1})	1.5 mg L^{-1}	1 mg L^{-1}
Magnetic powder (3,000 yuan t^{-1})	/	5 mg L^{-1}
Total costs	0.15 yuan m^{-3}	0.15 yuan m^{-3}

the tractive force produced by the magnetic field is much greater than that of gravity; therefore, the settling time of the flocs can be greatly shortened, which in practice can reduce the volume of the sedimentation tank, and the project investment will be greatly reduced [42,43]. Magnetic coagulation can be used to solve the problem of an increased amount of water in the advanced treatment stage because it can guarantee effective treatment without enlarging tank capacity and increasing reagent dose. Therefore, it is a feasible quality upgrade.

4. Conclusions

The optimum conditions for the treatment of coal chemical wastewater by magnetic coagulation were 80 mg L^{-1} magnetic powder, 40 mg L^{-1} PAC, 1.0 mg L^{-1} PAM and an initial pH value of 7.0. The average recovery rate of magnetic powder was 96.99%, and the properties of the recovered magnetic powder were still stable after repeated use.

Under the optimum treatment conditions, the removal rates of COD, turbidity and SiO_2 were 7.0%, 6.6% and 5.1% higher than those in conventional coagulation, respectively,

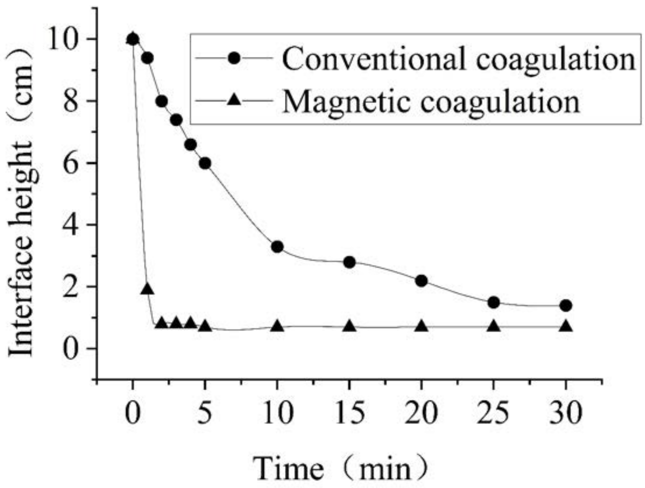

Fig. 8. Comparison of sedimentation rates between magnetic coagulation and conventional coagulation.

and the cost of magnetic coagulation was 26.6% less than that of traditional coagulation. The settling performance was remarkably improved: in conventional coagulation, sedimentation was stable in approximately 30 min, and the average sedimentation rate was 0.27 cm/min, while in magnetic coagulation, stability could be reached in approximately 2 min, and the average sedimentation rate was 3.85 cm/min, 14 times faster than that of conventional coagulation.

Magnetic coagulation was not only better than conventional coagulation in terms of the treatment effect but also had an obvious advantage in terms of sedimentation speed. Magnetic coagulation technology could effectively reduce the volume of the sedimentation tank and could achieve the desired treatment effect even when the amount of water to be treated increased. Therefore, it is feasible to use magnetic coagulation technology instead of conventional coagulation to improve the water quality standard.

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