Wet flue gas desulfurization wastewater treatment with reclaimed water treatment plant sludge: a case study

Hong Chen, Yiyu Wang, Yanxiao Wei, Liang Peng, Bo Jiang, Gang Li, Guanlong Yu and Chunyan Du

ABSTRACT

To upgrade a wet flue gas desulfurization (FGD) wastewater treatment process in a typical thermal power plant (TPP) in Hunan province, China, a new concept for reusing polyaluminum chloride (PAC)-based water treatment plant sludge (WTPS) as a coagulant is proposed. Results show that, for an optimal WTPS dosage of 1,000 mg/L, the corresponding removal capacities for suspended solids (SS) and chemical oxygen demand (COD) from the practical FGD wastewater were 58.3% and 40.3%, respectively. Through an advanced treatment with a dosage of 50 mg/L of PAC, pH of 9, and stirring of 150 r/min for 60 s and 50 r/min for 15 min, the total removal efficiencies of SS, COD, and total cadmium (Cd) from the FGD wastewater were 93.7%, 88.8%, and 84.6%, respectively. Therefore, a new modification process (that involves mixing with WTPS – slag cleaner – neutralization – coagulation – sedimentation) was proposed. The proposed process is economically superior, and the average cost for the FGD wastewater treatment was only 1.08 USD/t. This could provide a cost-effective alternative process for upgrading FGD wastewater treatment facilities of TPPs.

Key words | coagulation, recycle, resource utilization, water treatment plant sludge, wet FGD wastewater

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INTRODUCTION

Currently, coal provides a substantial amount of the Chinese energy supply. By the end of 2016, the thermal power capacity in the power structure of China was up to 4.29×10^{13} kWh with an annual increase of 2.4%. This was approximately 71.6% of the total electricity generation in China, of which 3.91×10^{13} kWh and as much as 91% was generated by coal-fired power plants, and there was an annual increase of 1.3% in the total electricity generation (CEPIA 2016). Pollution emissions from coal combustion (including sulfur dioxide (SO_2), nitrogen oxides (NOx), toxic volatile organic compounds, heavy metals, and particulate matter) can cause significant problems and even city haze in China (Zhang *et al.* 2015; Liu *et al.* 2016). Thermal power plants (TPPs) are primarily responsible for 50% of total SO_2 emissions, and hence TPPs face increasingly stringent regulations in terms of limiting pollutant release, especially with the amendment of Emission Standard of Air Pollutants for Thermal Power Plants (GB 13223-2011) and Environmental Protection Law of the People's Republic of China (2014 Revision). Therefore, TPPs must install additional desulfurization facilities or replace existing facilities with higher desulfurized efficiency to meet stringent regulations (Schreifels *et al.* 2012; Yu *et al.* 2018).

Wet flue gas desulfurization (FGD) equipped with a lime/limestone wet scrubbing system is highly efficient and reliable, and more practical than other control technologies, and so it is widely used in more than 90% of TPPs in China (Zhang *et al.* 2015). Meanwhile, the wet FGD equipment leads to the discharge of a large amount of FGD wastewater (up to 9.6×10^8 t/yr) (NBSPRC 2014; Li *et al.* 2015). FGD wastewater has some common characteristics, such as low pH of 4.5–6.5, a wide range of high salinity (20–50 g/L), high calcium and magnesium mineral contents, and high anion (SO_4^{2-}, Cl^-, F^-) concentrations. FGD wastewater also contains some heavy metals (Cd^{2+}, Hg^+), has high suspended solids (SS) concentration of 20–60 g/L, and

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is strongly caustic (Gostomczyk *et al.* 1991; Vendrup & Sund 1994; Nielsen *et al.* 1997). Zero liquid discharge facilities and processes in power plant operations have attracted the public interest, but the high capital cost prevents their practical application (Pakzadeh *et al.* 2014). However, due to its high mineral content, highly complexity, and nonbiodegradability, FGD wastewater treatment is in urgent need of cost-effective and widely-recognized practical technologies (Li *et al.* 2017; Paredez *et al.* 2017; Jia & Wang 2018).

Currently in China, FGD wastewater from TPPs is mainly treated using chemical precipitation, and a million tons of neutralizers, coagulants, and flocculants are depleted (Meng *et al.* 2008; Ma *et al.* 2016; Xia *et al.* 2017). This could cause some serious problems including extremely high infrastructure expense and operation cost, over consumption of resources, massive waste disposal, and environmental pollutions. Moreover, because of its complex manufacturing and poor management, FGD wastewater treatment systems always have some equipment malfunctions that severely hinder normal operation (Córdoba 2015).

Meanwhile, most TPPs in China have their own independent water supply system including coagulation, sedimentation, filtration or clarification, and disinfection units. The typical and most important step is that plenty of coagulants/flocculants (such as polyaluminum chloride (PAC) or ferric chloride ($FeCl_3$)) are added to accelerate agglomeration of remaining small and dispersed particles and colloidal substances in source water (Ahmad *et al.* 2016; Lee *et al.* 2014). Therefore, a large amount of water treatment plant sludge (WTPS) is produced, and residual coagulant or Al/Fe-rich components make up a considerable proportion of WTPS (Yang *et al.* 2014; Chen *et al.* 2015; Ahmad *et al.* 2016). WTPS disposal can also lead to some environmental risks, resource waste problems, and extra expenses (Nair & Ahammed 2015). There is wide interest in the reuse of WTPS in land-applications for agricultural or ecological purposes, in building use as brick and cement, or in coagulant recovery (Dassanayake *et al.* 2015). However, some factors still severely hinder WTPS development and application. Such factors include environmental risks from heavy metals, economic issues with respect to low recoverable components, social acceptance, and legislation (Liu 2016; Yang *et al.* 2017). Recently, reuse of WTPS on wastewater treatment processes has been demonstrated as a promising development because of its significant environmental and economic benefits (Zhao *et al.* 2014; Kacprzak *et al.* 2017). Unfortunately, few studies focused on the treatment of FGD wastewater from a TPP by using its own recycled WTPS.

In this paper, a case study regarding the feasibility of reusing WTPS for FGD wastewater treatment at the same TPP was first investigated on site. Batch tests for WTPS with additional PAC for promoting FGD wastewater treatment efficiency were then carried out. Finally, a modified FGD wastewater treatment process with an economical assessment was proposed. This can provide a specific reuse of WTPS to upgrade the whole wastewater treatment system of TPPs with both water supply and FGD wastewater treatment systems.

Filed investigation

In 2007, a TPP located at 28.48169 °N, 112.80355 °E was founded in Changsha district, Hunan Province, China. This TPP's first project was two 600 MW supercritical coal-fired power generating units that were simultaneously equipped with flue gas treatment devices.

FGD wastewater discharge and treatment

A wet FGD system was used for flue gas purification. Flue gas generated from a pulverized coal-fired boiler first entered an absorption tower where it was mixed with a counter-current lime slurry. Hence, contaminants (such as particles, SO_2, NO_X, heavy metals, HCl, and HF) in the flue gas were transferred into the absorbent via reactions with calcium hydroxide solutions; these reactions included absorption, dissolution, oxidation, and crystallization. The purified gas finally passed through a defogger and was emitted through a flue pipe outlet.

FGD wastewater is mainly produced via two routes. One route is plaster-rich wastewater produced by a lime slurry after adsorbing contaminants from the flue gas and a leachate that contains plaster, heavy metals, limestone, and sulfate from the dehydration unit. The other route involves flush water from the lime slurry tank and the power generating units, cooling water, and TPP sewage.

In 2015, total coal consumption of the case study TPP was 2.3 million tons, and the cumulative electrical energy generated was as high as 6 billion kWh. Meanwhile, the amount of wastewater discharged by the TPP was over 1.5×10^5 t/yr.

An existing process (that involved slag cleaner – clarification – neutralization – sedimentation – chemical precipitation) was used for FGD wastewater treatment, as shown in Figure 1.

FGD wastewater was collected in a mixing tank and pumped into a slag cleaner with backflow sludge from the

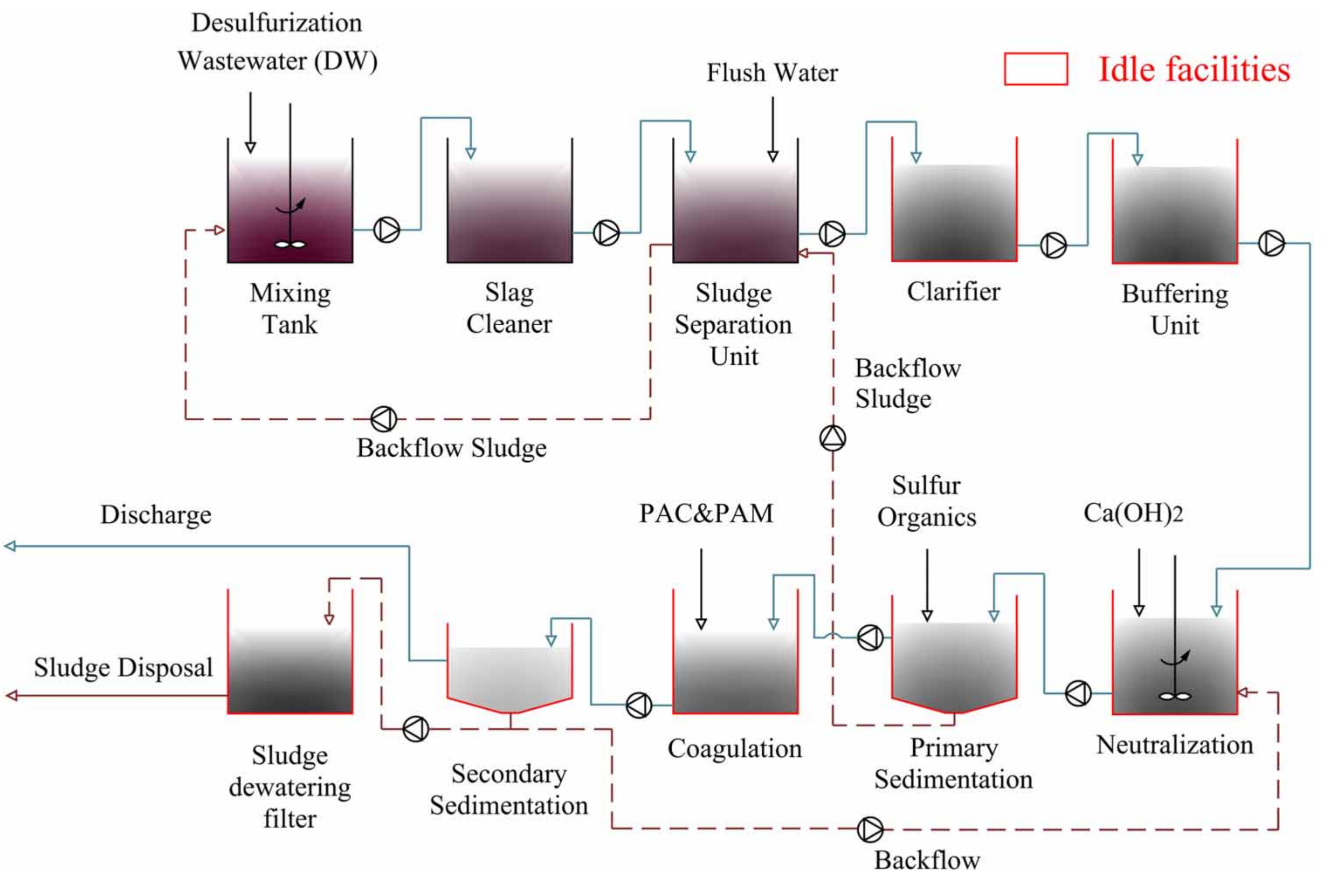

Figure 1 | Flow chart of the existing process for FGD wastewater treatment.

following sludge separation unit. The supernatant was then successively passed through a clarifier, buffering unit, neutralization tank (with added $Ca(OH)_2$), primary sedimentation tank (with accelerating sedimentation chemicals), and flocculation tank (with PAC and polyacrylamides (PAM)). Finally, purified water was discharged from a secondary sedimentation tank. Sludge from the primary sedimentation tank was pumped back to the sludge separation unit along with the flush water. Whereas sludge from the secondary sedimentation tank was injected into the sludge dewatering filter press except for partial backflow to the neutralization tank, in which the dehydrated sludge was disposed for landfilling, and the leachate was back flowed to the buffering unit.

Existing problems of FGD wastewater treatment

Unfortunately, in 2015, field investigation found that there are still some problems with existing FGD wastewater treatment facilities.

First, parts of the process stopped running. The FGD wastewater treatment system was simultaneously constructed and operated with the main part of the TPP in accordance with legislation requirements, in which incomplete applicable process and equipment were selected based on a predicted target water quality of FGD wastewater in the planning and design stage. As subsequent production and business adjustments, the boiler was filled with raw coal of low quality, and this caused a substantial change in the FGD wastewater. Thus, the selected long process flow with less applicability could easily cause extra expenses and increase operation cost (Córdoba 2015; Zhang & Liu 2015). Some considerable parts of the process idled or were at a low use frequency for their unavailability and inconvenience, including the buffering unit, neutralization tank, primary sedimentation tank, flocculation tank, secondary sedimentation tank, pump for sludge back-flow, injection pump for adding $Ca(OH)_2$, and sludge dewatering filter.

Second, there is an urgent need to optimize the parameters. Several chemicals were added at different treatment units, but there were confusions over optimal reagent types and their dosages as well as reaction conditions.

Third, there is immediate demand for effective operations strategies. A highly targeted expert plan using a strong response mechanism could be developed to cope with FGD wastewater fluctuations in water quality and some new emerging problems. Environmental protection accounts and checklists have not been strictly implemented for lacking complete and standardized operating procedures.

WTPS disposal

An attractive part of the TPP in the case study is that it has an internal water treatment plant (IWTP) with a capacity of 3×10^4 m^3/d. In the IWTP process, surface water from Xiangjiang River was pumped into the raw water distribution well and successively passed through a grid flocculation tank with added coagulant and an inclined plate sedimentation tank for WTPS removal. PAC was used for water purification.

A large amount of WTPS (15 m^3/h) was discharged from the IWTP. Moreover, WTPS (0.15 mg Al/mg WTPS) was not effectively treated and safely disposed; it was temporarily deposited in a reservoir with a volume of 140 m^3. Therefore, it is necessary to estimate the feasibility of WTPS reuse in terms of its recyclable potential (Hidalgo *et al.* 2017).

MATERIALS AND METHODS

WTPS and FGD wastewater sampling and characteristics

WTPS and FGD wastewater were separately taken from the WTPS reservoir and FGD wastewater mixing tank while the TPP operated under normal conditions. Except for temperature and pH (which were monitored on site), all indexes were analyzed at the laboratory. Because of standard and practical requirements, chemical oxygen demand (COD), SS, and total cadmium (Cd) were selected as key indexes of water quality. Characteristics of WTPS and FGD wastewater are listed in Table 1.

Table 1 | Characteristics of FGD wastewater and WTPS

Index	FGD wastewater	WTPS
Temperature (°C)	35.0	25.0
pH	7.18	7.54
COD (mg/L)	229.7	227.6
SS (mg/L)	15,041	4,014
Cd (mg/L)	0.134	0.071
Total solids (mg/L)	/	4,672

Note: FGD wastewater discharge limits in China for COD, SS and Cd were 100 mg/L, 70 mg/L and 0.10 mg/L, respectively.

Analytical methods

A portable pH meter (Seven2Go™, Mettler Toledo) was used for pH and temperature measurements. Chinese Standard Methods (GB11914-89) was employed for COD determination. Heavy metals were determined using atomic absorption spectrometry (Perkin Elmer, model AA700 Flame) with a wavelength of 228.8 nm. An electric blast-drying oven (FL-101, Flourish, Qingdao) was used for solids determination. A field emission scanning electron microscope equipped with an energy dispersive X-ray spectrometer (EDX) (SU8000, Hitachi) was used to analyze sample structural morphology under a landing voltage of 3.0 kV and WD of 1.5 mm. An X-ray diffractometer (XRD) (X'Pert PRO, PANalytical) was used for phase identification of WTPS samples with CuK_α radiation = 1.541 Å at 2θ over a range of 10° to 80° for a continuous scanning step length of 0.02°.

Batch tests

The ratio of WTPS to FGD wastewater was 16:84, in accordance with the field investigation and previous studies, which were used to validate effectiveness of WTPS on FGD wastewater treatment (Lee *et al.* 2014). In beaker tests, 500 mL of a mixture of WTPS and FGD wastewater mixture were stirred using a magnetic plate (Hang Lung, JB-4). After 3 min of mixing WTPS with FGD wastewater, and the mixture was allowed to settle for 30 min. The supernatant was tested to determine SS, COD, and heavy metal concentrations. Effects of WTPS dosages of 0, 500, 1,000, 1,500, and 2,000 mg/L on FGD wastewater treatment efficiency were then investigated.

Enhanced coagulation experiments using PAC (Gongyi Haiquan Co. Ltd, $A_2O_3 \geq 28\%$) addition were carried out for further treatment of FGD wastewater with added WTPS. Also, effects of PAC dosage (25–125 mg/L), pH (5–9), stirring intensity (50–250 r/min), and stirring time (5–25 min) on SS, COD, and Cd removal efficiencies of FGD wastewater were also investigated.

Economic evaluation

For WTPS reuse, key aspects must be considered, including technical applicability and economic practicability. Economic evaluation was defined as the comparative analysis of alternative courses of action in terms of both their costs and consequences (Xu *et al.* 2014). All items calculated for this project were provided in US dollar equivalency according to the Bank of China (BOC) exchange rates

(649.36 Chinese yuan (CNY)/100 United States dollar (USD) on Jan. 1, 2016). The net present value (NPV) method was used to evaluate investment expenses, operation costs, and benefits to compare the existing process with the proposed process using WTPS (Babatunde & Zhao 2007; Zhang *et al.* 2015). Three main parts were considered: (1) total investment (USD), (2) total cost of production (namely, annual operating costs (USD/yr)), and (3) environmental benefits (USD/yr).

In our calculations, the total investment includes all capital expenditures of the project renovation, such as construction expense and purchase and usage fees for facilities and equipment (consumption tax is not included). Annual operating cost (USD/yr) covers all costs for the process operation in one year, including equipment operation and overhaul expenditure; raw material costs for chemicals, water, electricity and compressed air; and employee fees and professional training (Kacprzak *et al.* 2017; Li *et al.* 2017). Environmental benefits are the total virtual expenses that must be paid for certain extra environmental pollutants, ecological damage, and resource extraction and consumption (Babatunde & Zhao 2007). There were three parts to the environmental benefits calculation: (1) equivalent emission reduction, (2) water reuse, and (3) other factors, such as a water fee for freshwater reservation.

RESULTS AND DISCUSSION

Batch tests to determine feasibility of reusing WTPS

Removal efficiency of FGD wastewater via mixing with WTPS

Effects of WTPS addition on SS and COD removal efficiencies of FGD wastewater are shown in Figure 2.

The removal efficiencies of both SS and COD increased with an increase in the WTPS dosage and reached maximum values with a WTPS dosage of 1,000 mg/L. However, both removal efficiencies slightly decreased with a further increase in the WTPS dosage (Figure 2). The maximum removal efficiencies for SS and COD were 58.3% and 40.3%, respectively. Although considerable removal of SS and COD from FGD wastewater was achieved merely with the addition of WTPS, the results are still insufficient for achieving target requirements.

Inorganic particles dominate the SS concentration of FGD wastewater and are easily removed via the addition of coagulants or flocculants. Reduced substances from the

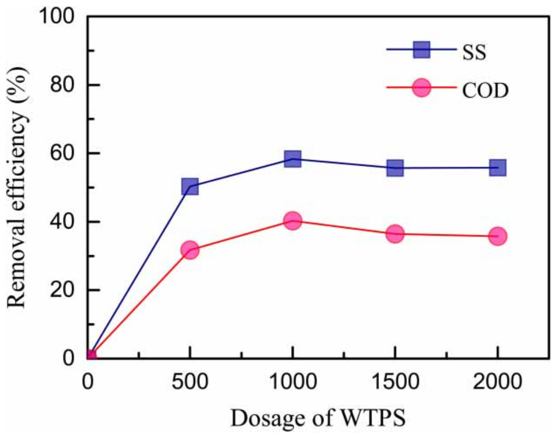

Figure 2 | Effects of WTPS addition on SS and COD removal efficiencies of FGD wastewater.

wet FGD unit and organic matter from sewage of the TPP are the main contributors of COD in FGD wastewater, which were difficult to remove by mixing FGD wastewater with WTPS. This result is consistent with the consensus that some coagulant residuals or active ingredients were still present in WTPS (Dayton & Basta 2005; Yang *et al.* 2014). The treatment performance was apparently influenced by the purity of coagulants (Keeley *et al.* 2014; Hidalgo *et al.* 2017), and the impurity of WTPS reclaimed from IWTP led to performance decline when WTPS adding dosage was increased from 1,000 to 2,000 mg/L.

Pollutant removal mechanisms using WTPS

Both WTPS and the sediment of WTPS mixed with FGD wastewater were analyzed by using scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDX) to explore the process mechanisms. The SEM-EDX morphology and composition results are shown in Figure 3.

Figure 3(a) shows a typical morphology of WTPS that consisted of many irregular and differently sized particles with many pores and rough surfaces. The huge surface area implies a good adsorption capacity and a good affinity for pollutants. The EDX spectrum (Figure 3(b)) shows that there is a considerable fraction of Al and a small amount of Fe present in WTPS, and the elemental chemical composition was as follows: O 42.43%, C 7.29%, Si 17.18%, Al 15.54%, Mg 0.72%, Fe 3.87%, S 0.00%, K 1.24% and Ca 1.24%. Field investigation confirmed that PAC was used as a coagulant in the water treatment process, and this study supports that WTPS has some active coagulant residuals (Keeley *et al.* 2014).

Figure 3(c) shows that sediment of WTPS mixed with FGD wastewater had a surface that was smooth and

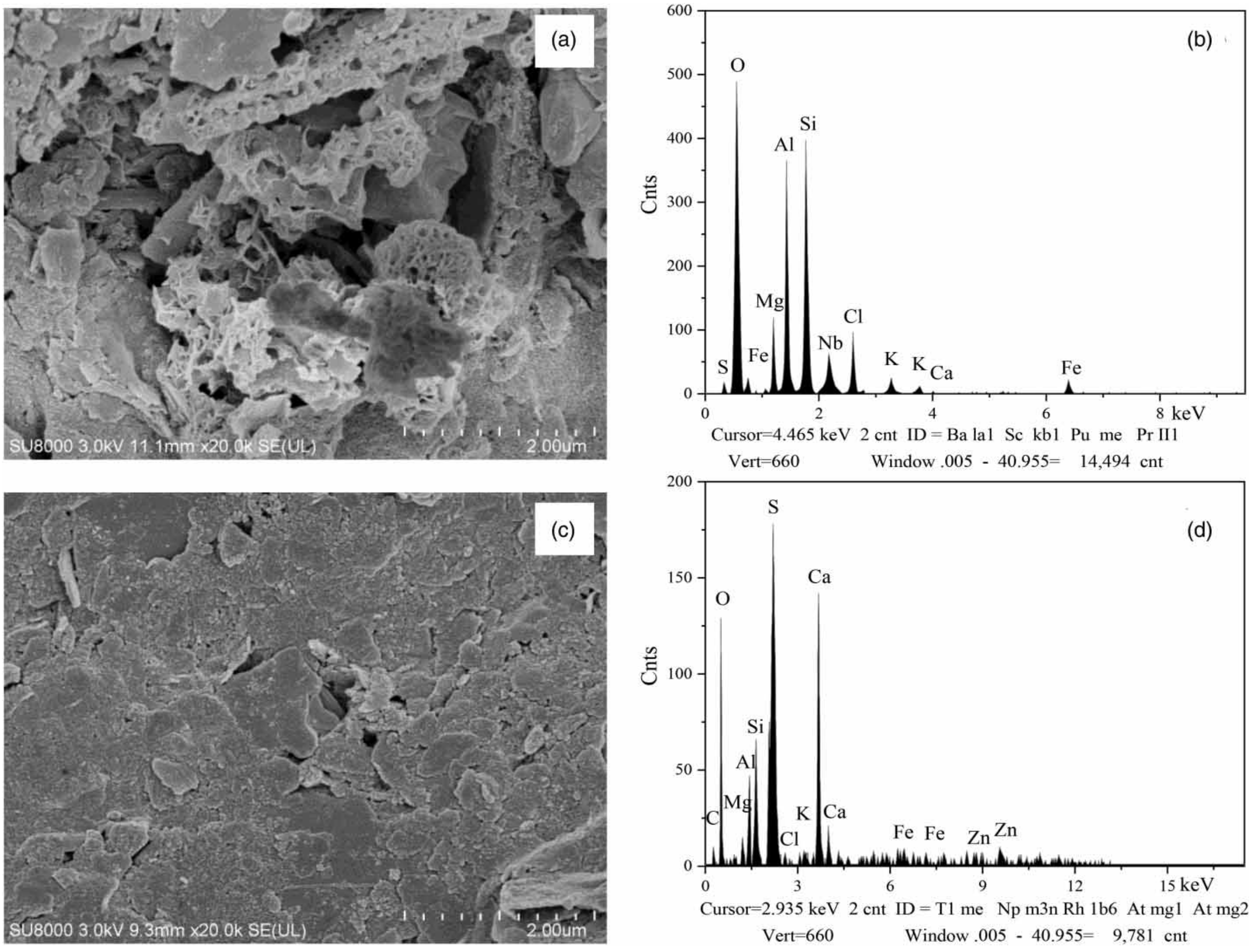

Figure 3 | SEM micrograph and EDX spectrum of WTPS (a) and (b) and sediment of WTPS mixed with FGD wastewater (c) and (d).

non-porous. In contrast to WTPS with scattered irregular particles, the sediment seems like a compact solid with some fissures. In addition, the corresponding EDX spectrum (Figure 3(d)) indicates a great decrease of Al and a dramatic increase of S and Ca in the sediment (the elemental chemical composition of the sediment: O 34.34%, C 3.94%, Si 4.83%, Al 3.78%, Mg 1.17%, Fe 1.46%, S 14.97%, Zn 4.71% and Ca 19.15%). The results were consistent with the main compositions of particles in plaster-rich wastewater (limestone and sulfate). Thus, the dense structure of the sediment can be attributed to overreaction of WTPS with particles in FGD wastewater (Yu *et al.* 2018).

Figure 4 shows X-ray diffraction patterns for WTPS and the sediment of WTPS mixed with FGD wastewater.

The XRD spectrum in Figure 4 shows that both samples contain complicated materials and clay minerals. $Al(OH)_3$ can be identified as the main form of active coagulant

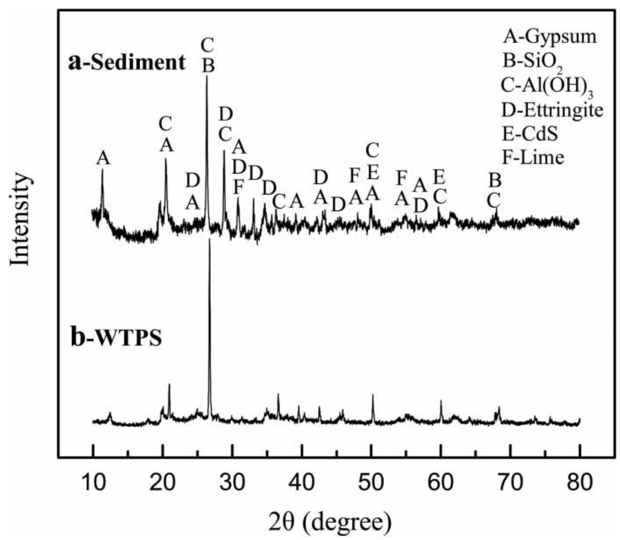

Figure 4 | XRD pattern of WTPS and sediment of WTPS mixed with FGD wastewater.

presented in the WTPS. The XRD pattern for the sediment has some new diffraction peaks that correspond to the crystal structures of gypsum and cadmium sulfide (CdS) (Zhao *et al.* 2014; Yu *et al.* 2018). Comparing peak position and intensity, further supports the contention that WTPS had a strong reaction with FGD wastewater. Therefore, this provides solid evidence of the feasibility of WTPS utilization.

Enhanced coagulation for advanced treatment of FGD wastewater

Chemical treatment of FGD wastewater was proved to have high effectiveness (Pasiecznik & Szczepaniak 2017). In batch tests for advanced treatment of FGD wastewater, effects of various factors (PAC dosage, pH value, stirring intensity of fast mixing, and stirring time of slow mixing) on SS, COD, and Cd removal efficiencies are shown in Figure 5(a)–5(d).

When the pH was increased from 5 to 9, SS removal efficiency first increased and reached a maximum at a pH of 7, and then it decreased slightly, whereas the COD removal efficiency had a significant decline point at a pH of 8. Cd removal efficiency was in a straight line with a slow increase (Figure 5(a)). The results were in agreement with that the high pH is in favor of precipitation of multivalent metal ions but against organics removal from FGD wastewater (Xia *et al.* 2017). With an increase in PAC dosage, removal

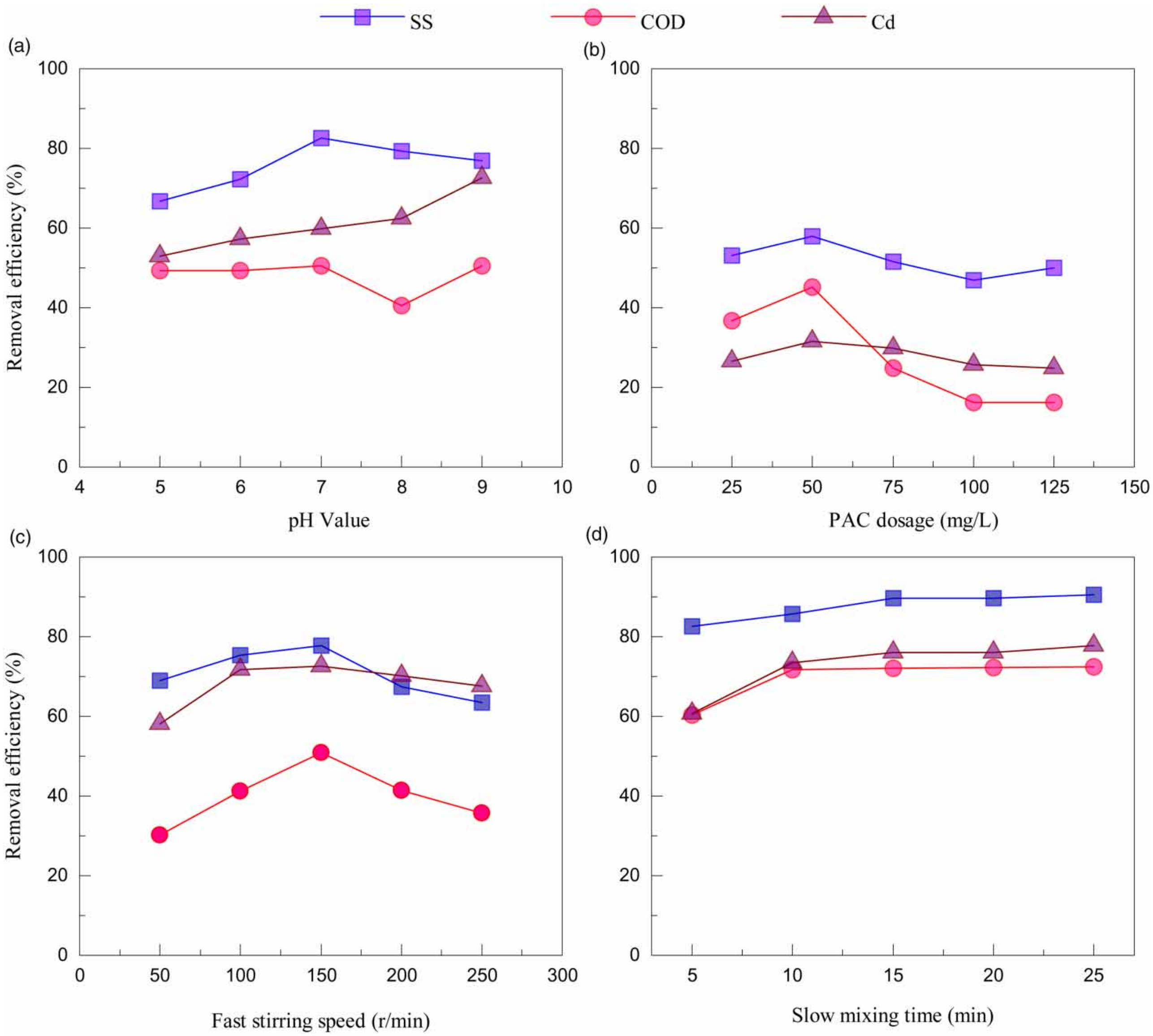

Figure 5 | Advanced treatment of the FGD wastewater by PAC coagulation.

efficiencies of SS, COD, and Cd first increased and then decreased slightly. At an optimal PAC dosage of 50 mg/L, SS, COD, and Cd removal efficiencies were as high as 57.9%, 45.2%, and 31.6%, respectively (Figure 5(b)). With an increase in the stirring intensity for fast mixing, the removal efficiencies of SS, COD, and Cd all had a similar increasing trend at first and then decreased. With 150 r/min as the optimal stirring intensity for fast mixing, SS, COD, and Cd removal efficiencies were as high as 77.8%, 50.9%, and 72.7%, respectively (Figure 5(c)). When the stirring time for slow mixing was increased from 5 to 25 min, removal efficiencies of SS, COD, and Cd all rapidly increased and then slowly increased. For practical consideration, 15 min was selected as the stirring time for slow mixing, and the COD, SS, and Cd removal efficiencies were 89.7%, 72.1%, and 76.1%, respectively (Figure 5(d)).

Although reclaimed WTPS has some uncertainties and risks (Liu 2016; Kacprzak *et al.* 2017), in this study, the removal efficiency with reclaimed WTPS and PAC fully meets the discharge standard (GB 13223-2011). For treating FGD wastewater from a power plant in a city in north China, a good removal efficiency was obtained under the conditions of polymeric polysilicate aluminium ferric sulphate dosage of 6.7 g/L, pH of 10, settling time of 20 min (Zhang & Liu 2015). In comparing a PAC dosage over 100 mg/L under similar conditions to samples with only PAC added, a dosage of 50 mg PAC/L FGD wastewater is greatly superior to FGD wastewater treatment when pretreated with WTPS. In summary, based on field investigation and batch test results, reuse of WTPS is technically reasonable.

Proposed modified process for treating FGD wastewater with reclaimed WTPS

With the aim of solving emerging problems of existing FGD wastewater treatments and the goal of satisfying new discharge requirements (Yang *et al.* 2017), the TPP in the case study submitted a request to upgrade the FGD wastewater treatment process based on established facilities. Considering cost-effectiveness and resource recycle, a modified process for FGD wastewater treatment was proposed in which WTPS was recycled for FGD wastewater treatment. The proposed flow chart is shown in Figure 6.

The modified process proposed that WTPS be primarily injected into a mixing tank to remove particles from FGD wastewater, and this can considerably reduce the loading rate of following units. Sediment was removed by a slag cleaner and sludge separation unit, and the supernatant was successively passed through a buffering unit, neutralization, coagulation, and secondary sedimentation tanks. $Ca(OH)_2$ was added to the neutralization tank, and PAC/PAM was added to the coagulation tank. Sludge from the slag cleaner, sludge separation unit, and secondary sedimentation tank was collected, concentrated, press filtered, and finally disposed.

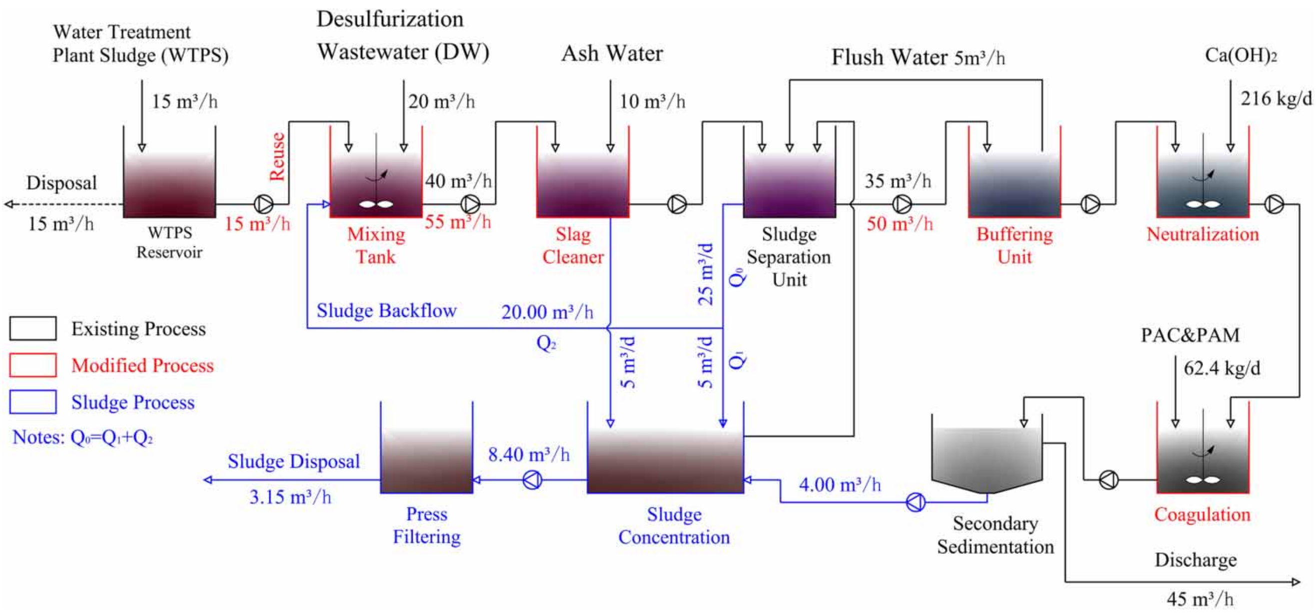

Figure 6 | Flow chart of the modified FGD wastewater treatment process.

Table 2 | Modified items for engineering demands in the proposed process

Item	Modifying or optimizing details	Engineering demands
WTPS reservoir	Dimension expanding from 140 m^3 to 248 m^3	Storage of the WTPS
Mixing tank	Mixing of the FGD wastewater with the WTPS with a WTPS/FGD wastewater ratio of 16/84, and with dimension 6.5 × 1.1 × 2 m.	Reuse of the WTPS for the FGD wastewater pretreatment
Slag cleaner	Renovate with 340 inclined plate and install an overflow pipe	Remove particles in big size and prevent overflow of the mixture
Buffering unit	Water flow direction changed to from bottom to surface	Optimization of clarification based on an optimal surface loading rate
Neutralization tank	Operation conditions under pH of 9, stirring speed of 150 r/min, stirring time of 20 min	Enhance heavy metals (Cd) removal
Coagulation tank	Operation conditions under PAC dosage of 50 mg/L, pH of 9, stirring speed of fast mixing of 150 r/min for 60 s, stirring speed of slow mixing of 50 r/min for 15 min	Ensure the effluent meeting with the discharge standards

Meanwhile, some modified items for engineering demands in the proposed process are listed in Table 2.

The WTPS reservoir was expanded to 248 m^3 in volume by adding an underground pool with dimensions of 8.4 × 4.5 × 3.0 m (L × B × H). Two sets of roots blower system were installed to prevent sludge caking on the bottom. A new mixing tank was constructed with dimensions of 6.5 × 1.1 × 2.0 m (L × B × H). In addition, operation parameters for the neutralization tank and coagulation tank were optimized to ensure that discharge standards are met.

Economic evaluation of the modified process with reuse of WTPS

Total construction investment

Some new equipment and construction were necessary for the modified process, and this increased the investment, as shown in Table 3.

Table 3 | Investment estimation for new equipment and construction

Name	Number	Type/model	Average price per unit[a] (USD)	Amount (USD)
Lift pump	2	100 HW – 5	2.77×10^3	5.54×10^3
Roots blower	2	BK8024	1.23×10^3	2.46×10^3
Hydraulic drive system	1	PARKER C3	1.85×10^3	1.85×10^3
Chemical dosing systems	1	Screw feeder R5	2.31×10^3	2.31×10^3
Mixing tank	2	15 m^3	6.46×10^3	1.23×10^4
WTPS reservoir reconstruction	1	248 m^3	2.31×10^4	2.31×10^4
Buffering unit	1	450 m^3	3.85×10^4	3.85×10^4
Total investment				8.61×10^4

[a]Includes all expenses for engineering construction, equipment installation and debugging and corresponding labor cost.

Expenses for the infrastructure construction were 7.39×10^5 USD, which was equivalent to about 85% of the total construction investment (8.61×10^4 USD). In our proposed plan, making maximum use of established facilities enabled strict control of the total investment.

Operating and maintenance costs

Operating and maintenance costs for electrical power consumption, chemicals consumption, direct labor cost, and maintenance cost were considered (NBSPRC 2014; CEPIA 2016; NDGP 2016), as shown in Table 4.

Expenses for electrical power and chemicals consumption were about 51% of total operating and maintenance costs. Chemical consumption for WTPS use was greatly reduced from 5.12×10^4 USD/yr to 2.50×10^4 USD/yr.

Environmental benefits

Equivalent emission reduction, water reuse, and water fee were accounted for in the environmental benefits of the proposed process. Values of all sub-items were estimated mainly on the basis of local policy and social economics (Babatunde & Zhao 2007; NDGP 2016; Kacprzak et al. 2017), as shown in Table 5.

Only emission fees for the main pollutant discharges (SS and COD) were calculated to evaluate the equivalent emission reduction according to the new standard for

Table 4 | Operating and maintenance costs

Item	Number or quantity (t)	Power consumptions or unit cost	Operating cost (USD/yr)
			Electricity power consumption
Lift pump	3	1.13×10^{2a}	3.21×10^4
Blower	1	2.03×10^{1a}	5.79×10^3
Mixer	3	3.05×10^{1a}	8.68×10^3
Sludge scraper	1	8.13^a	2.31×10^3
Mud discharge pumps	1	2.03×10^{1a}	5.79×10^3
Screw pump	2	2.90×10^{1a}	8.24×10^3
Filter press	1	2.71^a	7.71×10^2
Metering pump	3	3.39^a	9.65×10^2
Flushing pump	1	4.93^a	1.40×10^3
Feeding device	1	5.61^a	1.60×10^3
Amount			6.76×10^4
			Chemicals consumption
30% HCl	65	0.23^b	6.21×10^3
$Ca(OH)_2$	100	0.32^b	8.74×10^3
PAM	1.5	0.13^b	3.58×10^3
PAC	25	0.24^b	6.48×10^3
Amount			2.50×10^4
			Direct Labor Cost
Environmental engineer	2	7.70×10^{2c}	1.85×10^4
Skilled worker	4	6.16×10^{2c}	2.96×10^4
Department head	1	1.23×10^{3c}	1.48×10^4
Amount			6.28×10^4
			Maintenance Cost
Equipment overhaul	1	–	1.72×10^{4d}
Routine maintenance	1	–	8.61×10^{3d}
Amount			2.58×10^4
	Total: 1.81×10^5 USD/yr		

Unit: [a]kWh; [b]USD/t FGD wastewater; [c]USD/month (average); [d]USD/yr.

environmental tax in China; the total amount is 3.14×10^4 USD/yr. The reusing water amounts to 1.314×10^5 m^3/yr. According to the local water price and cost of wastewater treatment, the economic benefit from water conservation is 3.76×10^4 USD/yr. Additionally, according to the Water Law of the People's Republic of

Table 5 | Estimated environmental benefits

Item	Quantity (m^3/yr)	Value per unit (USD/m^3)	Benefits (USD/yr)
Equivalent emission reduction			
SS	3.23×10^4	0.86^a	2.78×10^4
COD	1.64×10^4	0.22^a	3.54×10^3
Amount			3.14×10^4
Water reuse			
Water reuse	1.314×10^5	0.29^b	3.76×10^4
Amount			3.76×10^4
Others			
Water fee	1.314×10^5	1.54×10^{-2c}	2.02×10^3
Amount			2.02×10^4
	Total: 7.10×10^4 USD/yr		

Source: [a]Standard of People's Republic of China Environmental Protection Tax Law (2017 Revision).
[b]Calculation from direct cost of FGD wastewater treatment and local price of tap water.
[c]Measures of Hunan Province on Administration of Water Permits and Water Resources Taxation (Hunan Provincial People's Government Decree No. 219).

China and local circumstances, the benefit from freshwater conservation in terms of a water fee is about 2.02×10^3 USD/yr. In summary, total environmental benefits from the modified process at the TPP was up to 1.02×10^5 USD/yr.

In the overall economic evaluation of the proposed process, FGD wastewater treatment costs 1.08 USD/t. The expenditure per unit by the new process is much cheaper than the average expenditure for FGD wastewater treatment (NBSPRC 2014; Jia & Wang 2018). Moreover, the environmental benefit was as high as 7.10×10^4 USD/yr. Therefore, the proposed process with WTPS reuse for FGD wastewater pretreatment in the TPP in the case study is economically superior.

CONCLUSION

A new concept for reusing the coagulant in the WTPS for pretreatment of FGD wastewater is proposed to overcome the shortages of existing facilities, including low treatment efficiency, high operation costs, and massive waste of resources in a typical TPP in Hunan Province, China. The new modified process involves mixing with WTPS – slag cleaner – neutralization – coagulation – sedimentation. Through WTPS recycling and maximally established facility and equipment utilization in the proposed process, both new investment fees and chemical consumption costs are greatly reduced, and the average cost for FGD wastewater treatment is only 1.08 USD/t. Moreover, extra environmental benefits can be up to 7.10×10^4 USD/yr. Based on field investigation, batch test result and economic evaluation, the recycling of WTPS for FGD wastewater treatment in the thermal power plant is not only technically reasonable but also economically superior.

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