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Performance characteristics of phosphorus removal in sewage treatment using electrocoagulation and fiber filtration process

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ABSTRACT

A study on an electrocoagulation method that can replace the existing phosphorus removal method was carried out. The problem with the existing electrocoagulation process was that the water is electrolyzed at the cathode and the hydroxide ion (OH^-) reacts with the iron ion to produce sludge. In addition, the final processing effluent is colored and creates an aesthetic problem. Therefore, a capable process is needed to solve the sludge and color generation problem in the electrocoagulation process. To minimize the sludge and color problems, a nonwoven diaphragm was installed between the steel plates of an electrocoagulation reactor, and a fiber filtration reactor was installed at the end of the process. The combination of electrocoagulation and fiber filtration processes demonstrated a stable water quality of total phosphorus (T–P) 0.15 mg L^{-1}, orthophosphate (PO_4–P) 0.08 mg L^{-1}, and suspended solids (SS) 0.02 mg L^{-1}. After the diaphragm installation, the sludge generation rate was decreased by 50%. Lastly, the backwashing point of the fiber filtration reactor can be determined by analyzing the correlation between the electrical conductivity (EC) of the final effluent and PO_4–P. As a result, the backwashing operation was effectively carried out. The backwashing operation can be controlled automatically by using the EC.

Keywords: Electrocoagulation; Electrical conductivity; Fiber filtration; Phosphorus removal; Nonwoven diaphragm

1. Introduction

As our standard of living has improved and developed, the generation of wastewater has increased. In response, nitrogen and phosphorus treatment processes have been developed, and wastewater treatment facilities are now being strengthened. As a result, phosphorus removal methods have been actively studied [1,2]. Typical removal techniques currently in use include biochemical and chemical treatments. Biological treatment methods produce less sludge than other treatment methods. However, it is difficult to maintain and operate the microorganisms, and the processing efficiency is relatively low [3]. Although chemical treatment methods have high treatment efficiency and high treatment speed, the disadvantages are that the method is not economical owing to the costs of chemicals and sludge disposal [4].

The electrocoagulation process can be considered as a method to solve this problem. In this study, the coagulation method was used and can achieve the same effect at a low cost. Nowadays the treatment method is being used in the various overseas wastewater treatment process [5–9]. Many studies, the electrocoagulation process has proven to be a useful process for wastewater treatment [10–12]. An electrocoagulation process was used as a pretreatment step for leachate treatment, which is difficult to treat owing to high pollutant emission [13], and the electrocoagulation process proved to be very useful for wastewater treatment with high concentrations of chromium residue [14].

In the case of electrocoagulation, water is electrolyzed in the cathode, and hydroxide ions (OH^-) react with iron

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ions to generate sludge. This leads to color generation in the final effluent (Eff) creating an aesthetic problem. Therefore, the treatment process needs to reduce the amount of sludge generated and color. In this study, the main purpose was to develop a process that combines electrocoagulation with a diaphragm, simple operation, economical methods, and water-washable fiber filtration.

2. Materials and methods

2.1. Operation of electrocoagulation reactor

The electrocoagulation reactor used in this study was a rectangular-column-type reactor made of acrylic, measuring 0.096 m in width, 0.1 m in length, and 0.15 m in height. And the total capacity was 1.44 L. In the coagulation reactor, a 0.002 m frame was inserted to allow the iron plate and a nonwoven diaphragm was installed. An airline was installed under the reactor for air injection for iron plate corrosion. Influent (Inf) wastewater was injected using a metering pump BT100-2J. The electrode plate was an SS400 model with good condition, 0.1 m width, 0.14 m length, and 0.002 m thickness.

Two electrode plates (a positive and a negative electrode) were installed in the coagulation reactor, and the gap between the two electrodes was set to approximately 0.01 m. The current supply to the electrode plate was a GPD-2302S model rectifier capable of converting voltages from a minimum of 1 V to a maximum of 30 V and capable of current conversion from a minimum of 0.1–3.0 A.

Electric current was supplied to the upper part of the steel plate using a connecting device by connecting a cathode to one steel plate and a positive electrode to the other steel plate. A nonwoven diaphragm having a width of 0.1 m, length of 0.15 m, and thickness of 0.002 m was inserted between the two electrodes. The nonwoven diaphragm reduced the sludge generated by inhibiting the binding of iron ions, the other than sludge usually generated by the combination of iron ions and phosphorus generated in the positive electrode and phosphate ions generated in the negative electrode.

The retention time was fixed at 20 min based on an existing research case [15]. The current was varied from 1 to 3 A, and the experiment was carried out. The voltage was continuously changed according to the fixed value of the current and the characteristics of the inflow water. A Wastewater treatment plant (WWTP) secondary sedimentation effluent was used as the process influent, and the voltage was operated in the range of 10 to 20 V. The current density was changed according to the voltage and current, and the range was 30–35 A m^{-2}. In order to examine the amount of sludge generated by the nonwoven diaphragm, all conditions were fixed, and experiments were conducted according to the presence or absence of the nonwoven diaphragm.

2.2. Operation of fiber filtration reactor

The fiber filtration reactor was a cylindrical reactor made by acrylic and consisting of an influent injection part, fiber filtration part, treated water discharge part, and backwashing water discharge part. The size of the reactor was 0.08 m in diameter and 0.35 m in height. About 1,200 pieces of hollow fiber yarn were cut into 0.1 m length, and then fixed with an aluminium rod as a supporting axis. The filling rate of the filter media was approximately 30%. In order to inject inflow water, a metering pump (Master Flux Easy-Load 7518-00 Model) was installed to flow upward.

In addition, a valve was installed in the reverse wastewater discharge line so that it could be discharged only after backwash. The purpose of the installation of the fiber filtration reactor was to solve the problem of sludge and color in the electrocoagulation reactor. The retention time was fixed at 20 min, which was the same as that of the electrocoagulation reactor.

Filtration was carried out at a rate of 25 mL min^{-1}. A diagram of the complete process is shown in Fig. 1. The fiber filtration effluent was always measured for EC to find the backwashing point. The backwashing operation method was executed when the EC value deviated from the normal range. Then, a mixer was turned on at 120 rpm for 1 min in both directions and 4 min to remove contaminants from the filter media. During the last 1 min, mixing and a reverse water supply were simultaneously carried out, and 2 L of fresh water was injected into the filtration reactor from top to bottom to remove contaminants.

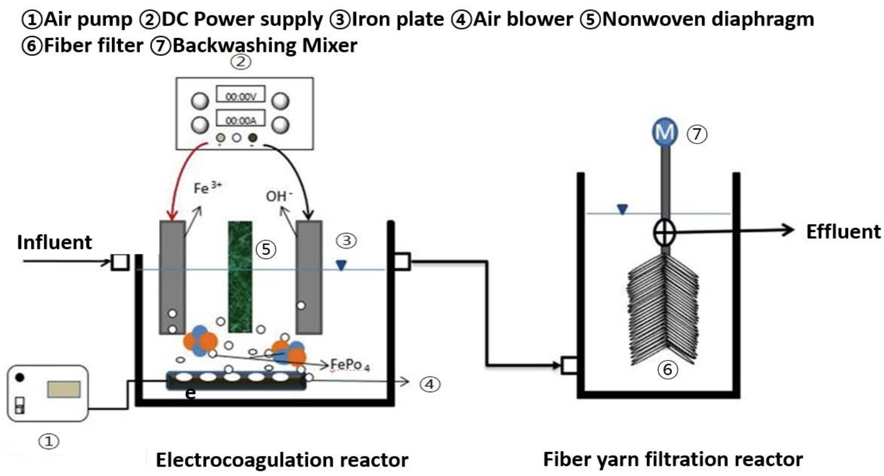

Fig. 1. Diagram of the process combining electrocoagulation reactor and fiber filtration reactor.

At this time, the backwashing water valve should be opened slightly, and the backwashing water should be backwashed by maintaining the water level of the filtration reactor by adjusting the flow rate of the backwashing water and the incoming fresh water. After confirming that the filtered water returned to the normal EC value within the initial EC range, the filtration reactor was operated again. If the EC has not returned to its normal range, it should be backwashed again to back its normal range (Fig. 2).

2.3. Influent characteristics and analysis method

The influent used in this study was secondary sedimentation treatment effluent from a biological sewage treatment plant at a WWTP. The characteristics of effluent were (Table 1) as follows: pH 7.01, T–P 1.82 mg L^{-1}, and SS 22.20 mg L^{-1}. The parameters pH and EC were measured and analyzed in real time. ORION STAR A221 and EC-40N were used for pH and EC measurement. In addition, the analysis methods of T–P, PO_4–P, and SS were analyzed based on the Korean standard water quality analysis method [16].

3. Results and discussion

3.1. Electrical conditions of electrocoagulation reactor

At first, all influence conditions were fixed, and the currents were changed to 1, 1.5, 2, and 3 A to compare the removal efficiency. As a result, high phosphorus removal efficiencies of over 92% were obtained under all current conditions. Among them, the removal efficiency was low (92.8%) when the current was 3 A, and high (97%) when the current was 1 A. Therefore, the most appropriate setting of 1 A was the optimum current intensity by judging the treated efficiency and economic efficiency.

In the next step, we set the appropriate current at 1 A and voltage to 5, 10, 15, 20, and 30 V. As a result, the voltage was also found to be higher than 92% in all cases. In all cases, when the medium voltage was 10 V, the highest efficiency of 99.4% occurred. Therefore, the appropriate voltage was determined to be 10 V. In this study, the voltage and current of the electrocoagulation reactor considering the influent characteristics were 1 A and 10 V. As in the study by Olmez-Hanci et al. [17], the experimental voltage and current can vary depending on the characteristics of the above gap mentioned influent and other incidental operation conditions.

3.2. Amount of sludge generated by nonwoven diaphragm

In this study, the main purpose of the nonwoven diaphragm installation is to reduce the sludge generation in the electrocoagulation reactor, that is, SS reduction. The electrocoagulation reactor was operated according to the presence or absence of the nonwoven diaphragm. The elapsed operating time of the electrocoagulation reactor was sampled and analyzed at 20, 30, 45, and 60 min. As a result, when the nonwoven diaphragm was installed, the amount of sludge generation was approximately 50% lower than before installation.

In the sludge generation test, the sludge generation rate per 1 m^3 of the secondary sedimentation effluent was estimated at approximately 1.9 g when the nonwoven diaphragm was installed, and approximately 3.8 g of sludge when the nonwoven diaphragm was not installed Fig. 3. In

Table 1
Characteristics of influent wastewater

Parameters	Range	Average
pH	6.17–7.98	7.01
EC (μS cm^{-1})	531–660	609
T–P (mg L^{-1})	0.79–3.65	1.82
PO_4–P (mg L^{-1})	0.46–2.57	1.38
SS (mg L^{-1})	12–38	22.20

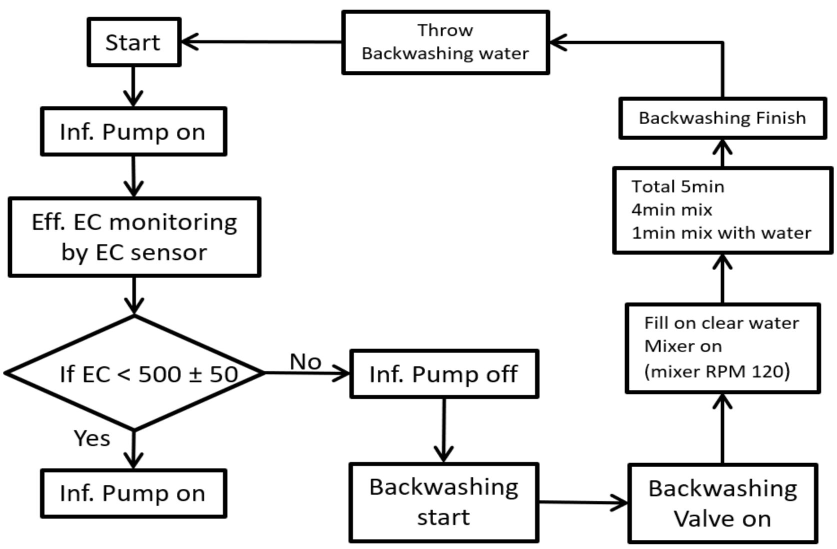

Fig. 2. Automatic control logic algorithm of fiber filtration using EC.

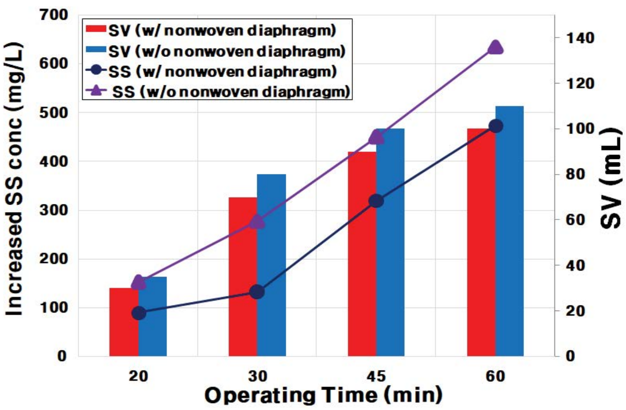

Fig. 3. Amount of sludge generated when nonwoven diaphragm was installed in electrocoagulation reactor.

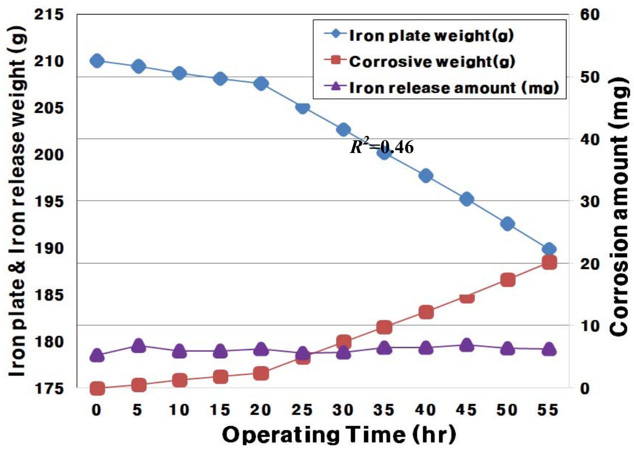

Fig. 4. Changes in weight of steel plates in relation to amount of iron during continuous operation.

order to reduce the sludge generation in the electrocoagulation reactor, a membrane was installed and treated [18]. In this study, the nonwoven diaphragm was installed between the iron plates of the electrocoagulation reactor to reduce the sludge generation from the iron plate.

The power cost for 1 month was calculated. And the cost was about 0.05 USD per kWh according to the standard of industrial power. The treatment flow rate was the same at 100 L d^{-1}. As a result, the power cost was 0.38 USD per month without a diaphragm, and increased to 0.58 USD (about 1.5 times) when a diaphragm was installed. However, the overall cost should be summed as the reduction of sludge (about a factor of half, 1/2) owing to diaphragm installation, associated treatment costs, and electrode replacement costs. The cost of the sludge treatment was considered as 88.81 USD per ton as the commissioned treatment standard, and the price of an iron plate was calculated as 0.89 USD per kg by referring to the price information. Considering the economic efficiency of the diaphragm installation with the total amount of sludge generation, power consumption, and corrosion of the steel plate, it was found that the diaphragm installation was more economical.

3.3. Electrocoagulation electrode plate corrosion rate and iron elution rate

The corrosion rate was determined by measuring the weight of the iron plate before the installation, and also the weight of the iron plate was measured by determining the interval of a certain period as the experiment was progressed. The weight of the steel plate was measured with a top balance (measurement limit: 0.01 g). The steel plate corroded at a rate of 17.14 mg dm^{-2} d (dm^2: width of a square of 1 dm, where 1 dm is a 10 cm, length of one side) of approximately 100 mg h^{-1} after the start of the operation, and started to accelerate at a rate of 85.71 mg dm^{-2}·d at a constant rate of approximately 500 mg h^{-1} after 25 h. After 20 h, the corrosion of the steel plate began in earnest (Fig. 4).

In order to investigate the removal characteristics of contaminants owing to corrosion of the iron plate, the corrosion weight of the iron plate and the weight of the phosphorus removal were calculated based on the phosphorus concentration. From 20 h after the iron plate operation time, the iron plate weight was corroded at 500 mg h^{-1}, and phosphorus was removed by approximately 2.7 mg per 20 min, that is, 8.1 mg h^{-1}.

The iron release rate was continuously analyzed by sampling every 30 min. As a result, in analyzing the iron release, the iron concentration was 4.23–6.25 mg L^{-1}, and the average concentration was 5.25 mg L^{-1}. The released mass was found to be constant at 7.57 mg, the same as the iron concentration. When this was calculated based on the area of the steel plate, the leaching rate of iron was 0.05 mg cm^{-2}, and the leaching speed of iron was 0.002 mg cm^{-2}·min. Therefore, 2.63 mg of iron were required to remove 1 mg of phosphorus.

3.4. Characteristics of pollutant treatment in electrocoagulation reactor and fiber filter process

The removal characteristics of phosphorus and SS in the electrocoagulation reactor were investigated. The influent T–P and PO_4–P concentrations were 1.5 mg L^{-1} or higher. After treatment in the electrocoagulation reactor, both T–P and PO_4–P stably maintained a concentration of 0.15 mg L^{-1} or lower, and the removal efficiency was higher than 94% (Fig. 5). On the other hand, the influent SS concentration was 23 mg L^{-1} on average, but the SS concentration was increased to 74 mg L^{-1} by sedimentation after treatment in the electrocoagulation reactor. This was removed in the fiber filtration process installed after the electrocoagulation reactor.

Therefore, in the electrocoagulation process, this indicates that an additional reactor process for removing SS is required at the subsequent stage. The effluent treated in the electrocoagulation reactor was filtered through a fiber filtration process to examine the removal characteristics of PO_4–P and SS. The filtration flux was maintained at about 300 linear height (LH), and the retention time of the fiber filtration tank was 20 min, which was the same as the electrocoagulation reactor. The operation was a continuous type and the water quality of the effluent treated in the fiber filtration reactor was stable within 0.15 mg L^{-1} of T–P and 0.08 mg L^{-1} of PO_4–P. The concentration of SS was 0.02 mg L^{-1} or lower and showed a very high treatment efficiency compared with influent. In

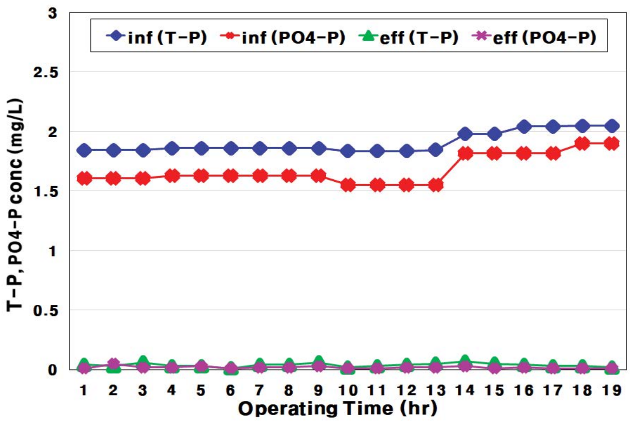

Fig. 5. Performance characteristics of T–P and PO_4–P in electrocoagulation process.

addition, no color was observed in the treated water of the fiber filtration process. These results show that the sludge problem and color problem in the electrocoagulation reactor were solved through the fiber filtration process.

3.5. Backwashing of fiber filtration process

The optimum backwashing period of the fiber filtration process was derived by using EC. A correlation between the EC and phosphorus concentration was reported [19], and the correlation coefficient between EC and the phosphorus concentration was very high at 0.94 [20]. In this study, the correlation between the PO_4–P concentration and the EC of treated water was analyzed and judged, and the backwashing point could be selected based on this analysis Table 2. The limit value of the concentration of effluent was set under

Table 2
Range of EC and PO_4–P concentration before and after backwashing

Parameters	Normal operation	Backwash operation
EC (μS cm^{-1})	450–550	>550
PO_4–P (mg L^{-1})	≤1.5	>1.5

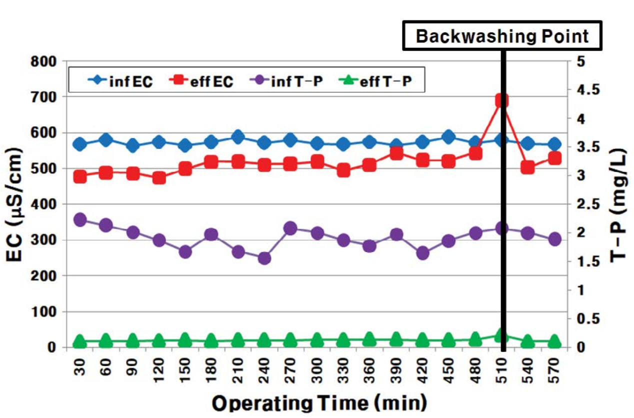

Fig. 6. EC and T–P change of influent and effluent in filtration process.

0.15 mg L^{-1}. As the process progressed, the EC value was increased, and the PO_4–P concentration was also increased. As a result, the fiber filtration tank was backwashed based on the sudden upward value of the EC. In addition, the PO_4–P concentration was analyzed before and after backwashing. The concentration was at 0.15 mg L^{-1} or higher before backwashing, and it was improved to 0.10 mg L^{-1} or lower after backwashing (Fig. 6).

4. Conclusions and recommendations

By providing a nonwoven diaphragm in an electrocoagulation reactor, the amount of sludge generation was reduced by approximately 50% compared with before the nonwoven diaphragm installation, thereby improving the economic and energy reduction effects in the sludge treatment process.

The phosphorus removal efficiency of the electrocoagulation reactor was 94% or higher, and both T–P and PO_4–P were treated to 0.15 mg L^{-1} or less, satisfying the water quality standard (0.2 mg L^{-1}) of discharged water for Korean sewage treatment facilities.

The concentration of treated water in the fiber filtration process was 0.15 mg L^{-1} of T–P and 0.08 mg L^{-1} of PO_4–P. The SS concentration of the treated water was 0.02 mg L^{-1}, which was much higher than the influent of the filtration reactor. In addition, the color problem in the electrocoagulation reactor was solved.

It was confirmed that PO_4–P was correlated with the EC of treated water in the fiber filtration process, and the backwashing point of the fiber filtration process could be set based on this correlation. As a result, the concentration of PO_4–P was improved to 0.10 mg L^{-1} or lower after backwashing and a concentration of 0.15 mg L^{-1} or higher before backwashing, thereby confirming stable backwashing efficiency. In addition, it is considered that the technology for the automatic control technology for the backwashing point using EC in the filtration process will be possible by utilizing the correlation between PO_4–P and EC.

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