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Development of activated carbon auto-regeneration system for water treatment filtration

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ABSTRACT

Activated carbon facilities for water treatment should be regenerated or changed because their adsorption capacities decrease with the passage of operating time. A novel system of activated carbon auto-regeneration system for water treatment filtration (ARWF), which has been recently developed, is capable of both operations of adsorption treatment and activated carbon regeneration simultaneously. Upon the adsorption, capacity of activated carbon has decreased to a certain level, the process of regeneration starts automatically. Regenerating process is operated by boiler, line heater, and spray which are located at nozzle pipe inside column. The process uses a super-heated steam of which temperature is 400–600˚C. Steam of 100–110˚C is generated by steam boiler and then super-heated steam of 400–600˚C is created by line heater. Super-heated steam is sprayed with activated carbon through spray nozzle pipe. A series of experiments were performed to evaluate the ARWF on the capacity of regeneration. The result showed that the ARWF was able to regenerate a used activated carbon almost same (98%) as a new carbon in terms of iodine adsorption. The values of iodine adsorption for original and 10 times regenerated carbons were 1,074 and 1,046 mg/g, respectively. In the removal of COD and BOD, the removal rate of new activated carbon was 80%, which was 5–10% higher than that of the first and second regenerated ones. The chromaticity and turbidity removal rate was higher in the regenerated carbon than in the new carbon.

Keywords: Activated carbon; Regeneration; Adsorption capacity; Super-heated steam; Iodine adsorption capacity

1. Introduction

Activated carbon process is widely used in water treatment plants and wastewater treatment plants to remove organic contaminants, chromaticity, odor, taste, ABS, etc. [1]. The contaminant adsorption treatment using activated carbon was introduced a long time ago in advanced countries, and the effects and feasibility of the technology have been verified. In water treatment plants in Korea, the activated carbon

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treatment for the removal of taste and odor is recognized as the best available technology (BAT) [2].

The activated carbon is the agglomeration of amorphous carbon with well-developed micropores. It is fabricated with wood, brown coal, anthracite, and coconut peel. It is an adsorbent that ensures a large internal surface area because molecule-sized micropores are formed during the activation process [3,4]. This adsorbent can have a minimum surface area of 1,000 mm^2/g. The functional group of carbon atoms on the surface applies the gravitation to the adjacent liquid or gas and adsorbs the adsorbate atoms. Therefore, activated carbon is widely used for filters, bleaching, deodorization, solvent recovery, and gas removal in diverse industries such as the tobacco manufactures, environment engineering (water and air quality), and food industries [5].

When the fluid passes through the fixed activated carbon adsorption device, the substance to be removed starts to come out of the outlet after some time. This condition is called the breakpoint. The existing adsorption facility stops the fluid from flowing in before the activated carbon reaches the breakpoint and is shifted to the standby adsorption tower, or replaces the activated carbon or transports it to another recycling facility to undergo regeneration before returning it into the adsorption tower, which is a very inconvenient method. The activated carbon is relatively expensive, but has limited ability to adsorb organic contaminants [6]. In addition, it must be regenerated after the operation of the activated carbon facility for a certain period, and its maintenance is difficult.

The commercialized regeneration technology is the high-temperature (700–1,000℃) regenerative furnace technology, which is similar to a manufacturing process. If the regenerative facility is installed on-site, the entire facility and maintenance cost is over 40–50% of the manufacturing process, and the off-site regeneration service without the regenerative facility costs about 70% of the new activated carbon price [7]. The off-site regeneration service is economical for small-scale water treatment plants and wastewater treatment plants, but the activated carbon manufacturers in Korea are not yet ready for the regeneration service and practically have no maintenance technology or workforce. Therefore, an economical regeneration process that can replace the existing thermal regeneration process and that is easy to maintain is urgently required [8,9].

The technology addressed in this study was recently developed as the activated carbon regeneration technology, which regenerates activated carbon that has exceeded the breakpoint using super-heated steam [10]. It adsorbs and volatilizes the organic matter adsorbed onto the activated carbon using steam super-heated to a 400℃ or higher temperature. The regeneration is conducted until the upper part of the activated carbon exceeds 300℃. This technology has the same performance as the existing thermal regeneration method, is easy to use, and has very low facility and maintenance costs.

In this study, the regeneration performance of the newly developed auto-regeneration system for water treatment filtration (ARWF) that uses super-heated steam was evaluated. In addition, a pilot-scale advanced water treatment facility with ARWF was installed in an actual water treatment plant to examine the efficiencies of treatment and regeneration.

2. Regeneration mechanism

Fig. 1 shows the activated carbon regeneration mechanism. If water constantly flows for a certain period, the pores in activated carbon are saturated with organic matter, and the activated carbon reaches the breakpoint. Then, the regeneration system starts operating. First, 100℃ steam is generated from the steam boiler and converted into 400–600℃ super-heated steam through the line heater. The converted super-heated steam is injected into the activated carbon within the effective radius through the nozzle in the tower to raise the temperature of the activated carbon. Due to the 400–600℃ super-heated steam injection and temperature rise of the activated carbon, the moisture in the pores evaporates, and the adsorbed organic matter is removed through the desorption, volatilization, and decomposition due to the super-heated steam. The regeneration is completed when the activated carbon temperature exceeds 300℃, and the regeneration time depends on the capacity [11].

The boiling points of the organic matter adsorbed onto the activated carbon to saturate its pores are mostly low, at 400℃ or less. Accordingly, if at least

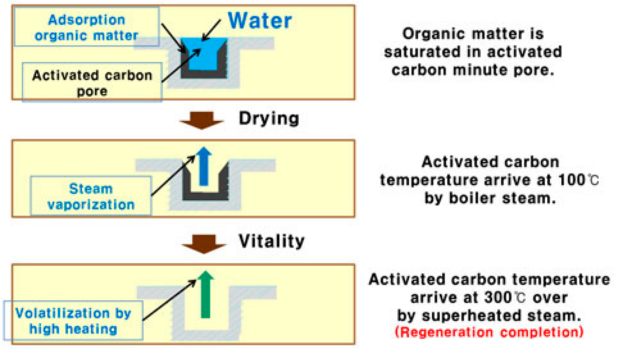

Fig. 1. Mechanism of activated carbon regeneration.

400˚C super-heated steam is injected into such organic matter, most of them will be decomposed and separated as liquid or gas [12]. In the case of biodegradable organic matter, 90% or more of them is reportedly removed by the at least 400˚C super-heated steam. Therefore, at least 400˚C super-heated steam is sufficient for activated carbon regeneration.

The activated carbon filtering system generally has more adsorption towers as the treatment capacity increases. The minimum number of adsorption towers is two, and one or more spare adsorption towers for regeneration are required [13]. When a certain amount of influent has flown and the activated carbon has reached the breakpoint, the regeneration system starts the regeneration operation. In case there are four towers, including a spare tower, water flows through Towers 1, 2, and 3, and the spare tower is on standby mode, as shown in Fig. 2. When the regeneration cycle starts, the regeneration is sequentially conducted starting from Tower 1, and the water flows through the spare tower only during the regeneration period. After the regeneration, the spare tower reverts to the standby state. This cycle is automatically repeated. The properties of the raw water and the equilibrium activated carbon adsorption quantity determine the regeneration cycle, within which the regeneration of all the towers are completed. To reduce the regeneration time, the drying process can be performed using a blower before the regeneration.

3. Methodology

3.1. Regeneration device and method

As shown in Fig. 3, the ARWF consisted of the adsorption system, which included the raw water tank, pump, and adsorption tower, and the regeneration system, which included the steam boiler, line heater, super-heated steam injection tube, and control panel. The raw water tank was prepared to keep the flow rate of the influent constant. The pump capacity, number and capacity of towers, and activated carbon layer height were determined according to the throughput per day. The heating value and the required steam quantity were considered in the establishment of the regeneration system. The regeneration system had a steam boiler, a line heater to raise the steam temperature to the regeneration temperature (400–600˚C), and an injection tube that allowed the injection of the super-heated steam into the tower.

The secondary effluent of the wastewater treatment plant was continuously injected into the activated carbon adsorption tower. The flow was stopped when the effluent/influent (C/C_0) concentration reached 0.7 (TOC), and then the regeneration was conducted. For the regeneration, high-temperature super-heated steam was injected into the adsorption tower through the tube injection nozzle to regenerate the activated carbon, after which the water flowed again. This cycle was repeated for the operation. A pump was used to inject the treated water from the wastewater treatment plant into the device, and the regeneration was conducted when it reached the breakpoint. During the regeneration process, the steam boiler generates 100˚C steam, which is heated to 450˚C when it passes through the heater. Sometime, after the super-heated steam is injected into the upper, middle, and lower parts of the activated carbon through the jet nozzle, the organic matter is removed and the activated carbon is regenerated. In this study, when the upper and middle parts of the activated carbon reached 300˚C, it was determined that the regeneration was completed.

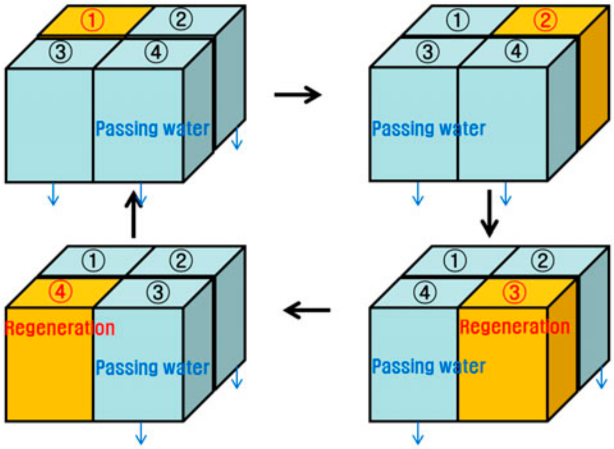

Fig. 2. Regeneration method in 4 adsorption towers.

3.2. Test materials

The secondary effluent of the S wastewater treatment plant was used as the raw water in this study. Table 1 shows the characteristics of the raw water. Norit GAC 1020 (Norit, USA) and Norit RO 0.8 (Norit, USA) were mixed at a certain ratio (7:3) for the activated carbon. Table 2 shows the characteristics of the activated carbon.

3.3. Analysis method

To evaluate the adsorption performance of activated carbon, an iodine adsorption test was conducted. The iodine adsorption capacity is the index of the quantity of iodine (mg) adsorbed onto 1 g of

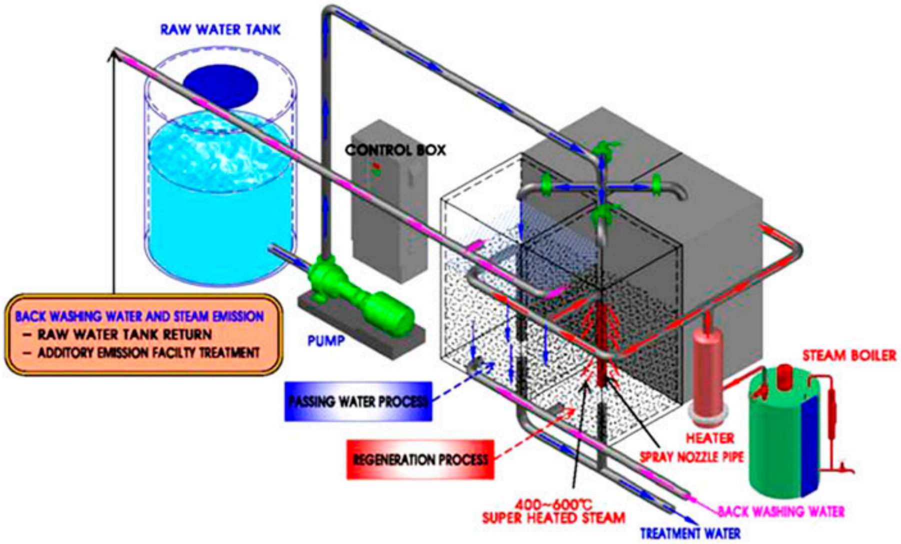

Fig. 3. ARWF used in this study.

Table 1
Characteristics of influent for pilot plant

Item	Range	Average
pH (–)	6.67–7.35	6.98
Temperature (°C)	15.8–23.50	22.59
DO (mg/L)	6.70–7.71	7.00
SS (mg/L)	1.37–2.45	2.04
TOC (mg/L)	5.21–9.19	7.59
BOD (mg/L)	1.79–5.73	3.81
CODmn (mg/L)	4.26–10.03	7.82
T-N (mg/L)	5.9–8.0	7.17
T-P (mg/L)	0.7–1.7	1.25
Turbidity (NTU)	0.98–5.45	1.88
Color (°)	25.01–38.70	33.84

Table 2
Characteristics of tested activated carbon

Parameter	Norit GAC 1020	Norit RO 0.8
Type	Granular	Pellet
Iodine number (mg/g)	1,050	1,175
Total surface area (m^2/g)	1,150	1,300
Apparent density (kg/m^3)	480	400
Hardness (%)	97	98
Ash content (mass %)	6	7
Particle size (mm)	0.85–2.00	<0.8
Uniformity coefficient	1.4	–
pH	Alkaline	Alkaline

activated carbon when the remaining iodine concentration after the filtration is 0.02 N [14]. Another indicator of the adsorption capacity of activated carbon is the specific surface area, which is calculated from the nitrogen adsorption quantity using BET [15].

Activated carbon must be very hard to reduce its loss before and after the regeneration in the activated carbon facility. In this study, the hardness of new carbon and regenerated carbon were analyzed. To analyze the processing efficiency of the activated carbon facility, qualities of the raw water and the treated water were analyzed in terms of TOC, BOD, COD, SS, T-N, T-P, and chromaticity. The hardness and water quality analysis items were analyzed according to the Standard Water Pollution Analytical Method.

4. Results and discussion

4.1. Treatment efficiency according to the activated carbon regeneration

Fig. 4 shows the COD and BOD ratios of the influent and the effluent for the evaluation of the organic matter removal characteristic according to the activated carbon regeneration. The COD and BOD removal rates were similar. The initial COD removal rates were 80% in the new carbon, and 65 and 90% in the first and second regenerated carbon, respectively. Accordingly, the removal rate of the new carbon was 15% higher than that of the first-regenerated carbon in the initial stage. The removal rate of the second-regenerated carbon was 10% higher than that of the new

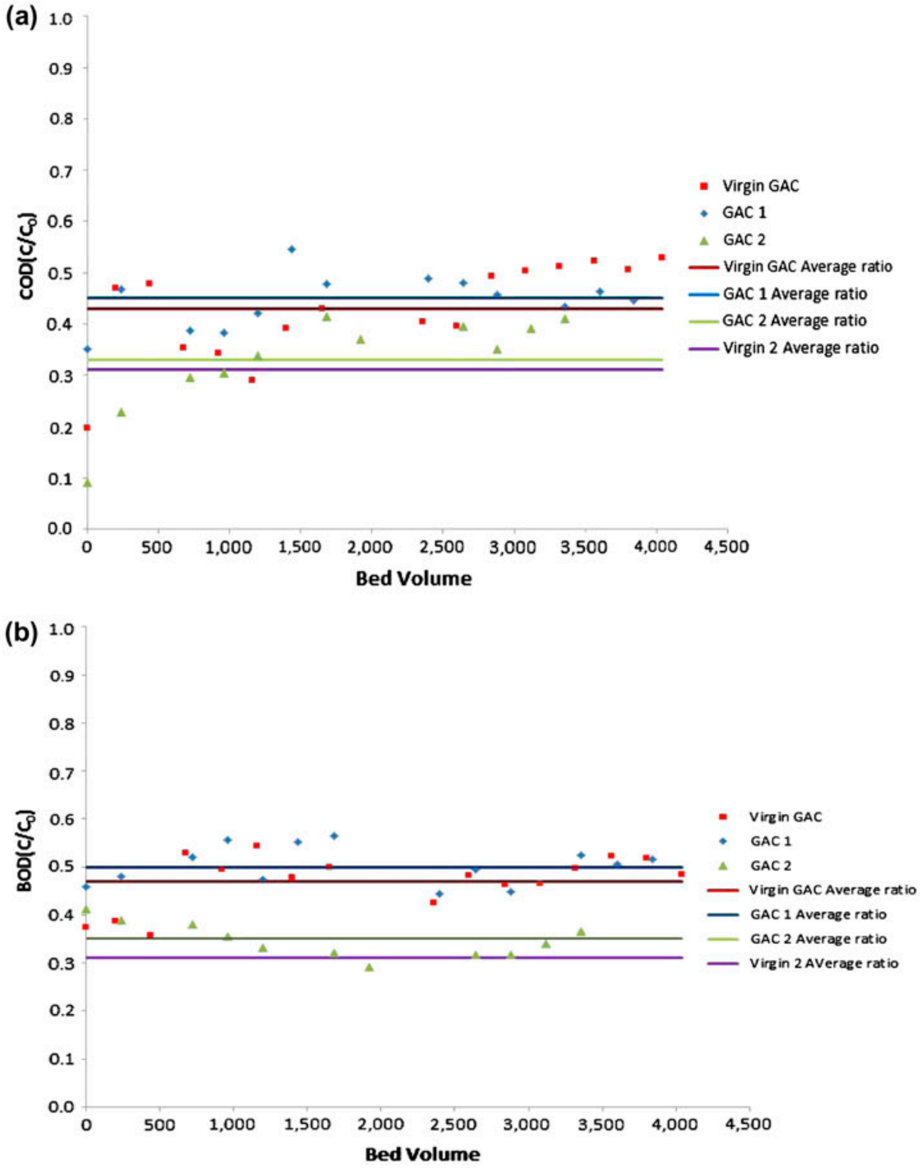

Fig. 4. Breakthrough curves of virgin and regenerated GAC for (a) COD and (b) BOD.

carbon. This was because the initially loaded new carbon was used to inspect the flow and regeneration process to check if the ARWF was properly installed, after which it was dried and used for the test. It seems that some carbon was replaced with new carbon during the activated carbon mixing/filling process due to the loss of activated carbon and the internal tower pressure after the second regeneration, which led to a high removal rate. The BOD removal rate was 6 3% in the initial operation stage in the new carbon (virgin 1), and about 54% in the first-regenerated carbon. Thus, the new carbon had a higher removal rate in the initial operation stage than the first-regenerated carbon. The second-regenerated carbon also had a higher removal rate than the new carbon, seemingly because of the COD removal rate tendency.

The activated carbon is known to be very efficient in removing chromaticity and turbidity. Some wastewater treatment plants discharge chromaticity and turbidity substances without treating them properly, and the activated carbon process can be used to address this problem [16]. In this study, the chromaticity and turbidity removal efficiency was analyzed with the second-treated water of the S wastewater treatment plant (Fig. 5). As shown in the figure, the chromaticity and turbidity removal rate was higher in the

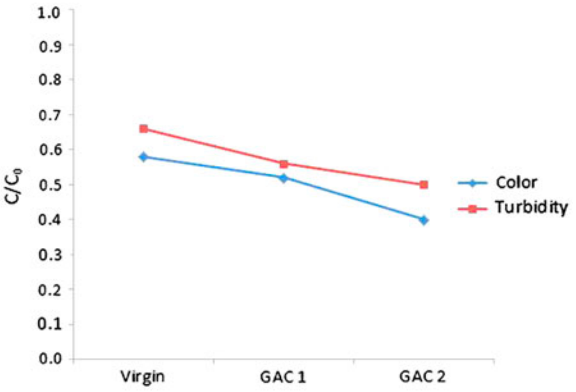

Fig. 5. Average ratio of influent and effluent in terms of color and turbidity.

regenerated carbon than in the new carbon. Regeneration blocks micropores, which leads to the development of macropores and mesopores. It seems that the development of large pores raises the removal rate because the chromaticity and turbidity substances are middle/high molecular substances [17].

4.2. Physical characteristics according to the activated carbon regeneration

The adsorption performance of the activated carbon was evaluated in terms of its iodine adsorption capacity, specific surface area, and micropore size. A high iodine adsorption capacity and a large specific surface area generally represent good adsorption performance [18]. Table 3 shows the test results of the activated carbon performance before and after the carbon regeneration. The specific surface area and micropore size results were also higher after the regeneration, which indicated that the carbon regeneration restored the adsorption capacity. In addition, 4-nm micropores were most abundant in the activated carbon before and after the regeneration. The micropore distribution was sometimes irregular in the new carbon and the activated carbon before the regeneration, but the micropore distribution was uniform after the regeneration, and the adsorption efficiency improved.

Table 4 shows the adsorption performance and the regeneration efficiency of the new and regenerated carbon using the 10-times-regenerated activated carbon. These are the results of the test of the activated adsorption performance (iodine adsorption capacity and methylene blue decolorization) and the regeneration (hardness). The iodine adsorption capacities of the new carbon and the regenerated iodine were 1,074 and 1,046 mg/g, respectively, which indicated that the adsorption capacity of the 10-times-regenerated carbon was not lower than that of the new carbon. The regeneration efficiency was approximately 98%. The results of the test of the hardness of the activated carbon, an important factor of regeneration, showed that the hardness was 99.8% in both the new carbon and the 10 times regenerated carbon. Thus, the hardness was not lost after the regeneration, and there was hardly any weight loss.

Table 3
Test results of activated carbon performance before and after carbon regeneration

	Iodine adsorption number (mg/g)	Surface area (m^2/g)	Average pore size (nm)
Activated carbon (Before regeneration)	839.5	948.0979	2.21647
Activated carbon (After regeneration)	836.2	949.7759	2.34341
Regeneration efficiency (%)	98.4		

Table 4
Comparison of activated carbons (new vs. 10 times regenerated)

	Iodine adsorption number (mg/g)	Methlene blue decoloration (ml/g)	Hardness (%)
Activated carbon (New)	1,074	200	99.8
Activated carbon (Before regeneration)	826	120	–
Activated carbon (After 10 times regeneration)	1,046	200	99.8
Regeneration efficiency (%)	98%		

5. Conclusion

In this study, the ARWF was used to examine the organic matter and chromaticity/turbidity removal characteristics and the physical properties of activated carbon after its regeneration. The following conclusions were reached by comparing the results with those of the existing activated carbon process.

(1) In the organic matter removal such as COD and BOD, the initial removal rate was 80%, which was 5–10% higher than that of the first- and second-regenerated carbon. The chromaticity and turbidity removal rate was higher in the regenerated carbon than in the new carbon, which resulted from the fact that the regeneration blocks micropores leading to the development of macropores and mesopores.

(2) The iodine adsorption capacities of the new and regenerated carbon differed only slightly. The iodine adsorption capacity recovery rate gradually decreased as the regeneration was repeated. In addition, the specific surface area, total micropore volume, and hardness decreased as the regeneration was repeated, and the mean micropore size gradually increased.

(3) The regeneration efficiency was approximately 98% and the hardness remained 99.8% after 10 times regeneration by the ARWF.

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