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A multihydrocyclone water pretreatment system to reduce suspended solids and the chemical oxygen demand

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ABSTRACT

We experimentally demonstrated that a multihydrocyclone water pretreatment system consisting of three serially connected hydrocyclones reduced suspended solids, the chemical oxygen demand (COD), and the biological oxygen demand (BOD) in muddy seawater and sewage samples. The separation efficiency of the hydrocyclones asymptotically decreased in accordance with the number of hydrocyclone treatment steps. The difference in the variation in the separation efficiency of the samples was caused by variations in the particle density and the radius of the mud and sludge particles. The multihydrocyclone pretreatment system purified the muddy seawater and sewage at a uniform purification speed of about 500 ton/d. The results suggest that the multihydrocyclone system provides an effective environmentally friendly method water pretreatment system, without any chemical processes.

Keywords: Hydrocyclone; Water pretreatment; Suspended solids; Chemical oxygen demand

1. Introduction

Wastewater (e.g. from human waste and industrial sites) and water from various sources (e.g. urban rainfall, seawater, river water, and groundwater) can be recycled in wastewater treatment systems [1–4]. Wastewater treatment systems make it possible to remove contaminants from wastewater by physical, chemical, or biological processes and provide clean water for drinking, washing, agriculture, food processing, and other uses [1–3]. Wastewater treatment systems consist of several pretreatment steps: primary treatment, secondary treatment, and reuse or disposal [5]. Generally, the pretreatment process uses solid disks and textile filters to remove contaminants, such as suspended solids, in wastewater [6,7]. However, these filters have to be changed periodically because they become blocked by contaminants during the pretreatment process [5]. In other words, the solid disks with the textile filters produce additional wastes because the filters degrade over time.

Cyclone or hydrocyclone separators without a solid disk and textile filters are widely used to remove particulates from air, gas, or liquid streams [8–11]. The high rotation speed of the fluid formed by the cylindrical structure of the cyclone separators separates particulates in air, gas, or liquid streams by the difference in their centrifugal forces [8–11]. The separation efficiency of cyclone or hydrocyclone separators is greater for particles larger than the cut point defined by their geometry [11]. Contaminated disks and textile filters often induce the overload of the water pumps resulting from the increase of the pressure in wastewater [12,13]. In contrast to systems that use disks and

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textile filters, uniform pressure can be maintained in hydrocyclone-based systems during the treatment process [8–11]. Thus, the water pumps used in hydrocyclone systems are more stable than those used in disk and textile filter-based systems. Another advantage of hydrocyclone filters is their long lifetime compared to that of disk and textile filter-based systems [11]. A number of recent studies have investigated numerical models of hydrocyclones based on the Navier–Stokes equation, with the aim of clarifying the main aspects of swirl flow problems in hydrocyclones [14,15]. An experimental study of hybrid hydrocyclones utilizing the injection of microbubbles revealed that they increased the separation efficiency and the removal of suspended solids [16].

In this work, we investigated the separation efficiency of a multihydrocyclone system in the pretreatment of muddy seawater. We experimentally confirmed the separation efficiency of this system, which includes three hydrocyclones and microbubbles injection, and its ability to reduce suspended solids in muddy seawater and sewage, in addition to the chemical oxygen demand (COD) and biological oxygen demand (BOD).

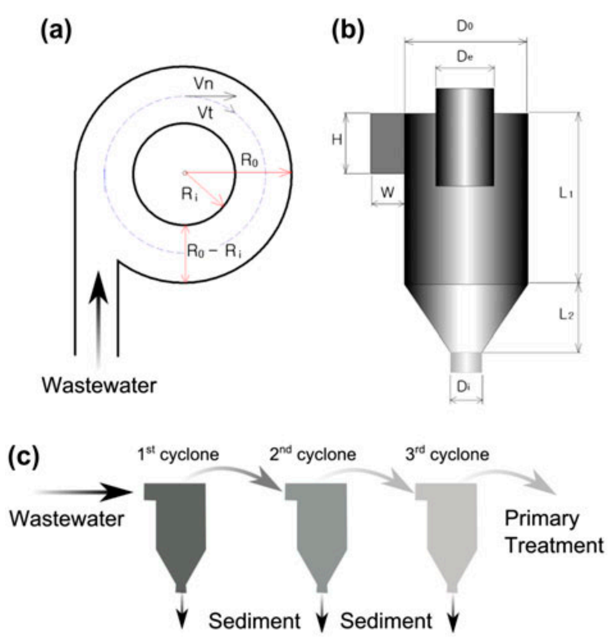

Fig. 1. (a) Horizontal section of a cyclone, (b) vertical section of a cyclone, and (c) multihydrocyclone water pretreatment system consisting of three cyclones. Microbubbles were injected in the first cyclone to remove floating material in the wastewater.

2. Materials and methods

Fig. 2 presents a schematic of the hydrocyclone separator. As shown in Fig. 1(a), wastewater is injected along the tangent line of the circle [9]. Thus, it is possible to centrifuge the wastewater by the rotational motion of the wastewater induced by the shape of the hydrocyclone. Mixing particles with a density of $\rho_p$and a diameter of d_p with a liquid having a density of ρ_a and a viscosity of μ yield V_n (the centrifugation speed) related to V_t as follows [9,17]:

$$V_n = \frac{{d_p}^2(\rho_p - \rho_a){V_t}^2}{18\mu R} \tag{1}$$

From this relation, it is inferred that it is easy to remove particles with a higher density from the liquid in the hydrocyclone system and more difficult to remove low-density particles. Thus, to remove the low-density particles adsorbed at the surface of the pipe and the hydrocyclone, we introduced a microbubble system. This supplied bubbles with diameters of roughly 10 μm in the first hydrocyclone, as schematically shown in Fig. 1(c). The separation efficiency of the hydrocyclone depends on the centrifugation speed and the dimensions of the hydrocyclones themselves. The particle diameter required to provide separation efficiency of 50% in the hydrocyclone system can be obtained as follows [10,18]:

$$d_{p50} = \sqrt{\frac{9\mu B_e}{2\pi N_e V_t(\rho_p - \rho_a)}} \tag{2}$$

where B_e is the width of the inlet, N_e is the number of rotation for the liquid from the inlet to the drain, and N_e is determined by the dimensions of the hydrocyclone.

$$N_e = \frac{1}{H}\left(L_1 + \frac{L_2}{2}\right) \tag{3}$$

In Eq. (4) below, d_{p50} determines the optimum dimensions of the hydrocyclones for the filtration of the target particles. In the system, we used two types of hydrocyclones, one with an area of 1.5 × 2 mm and one with an area of 5 × 10 mm at the entrance (Table 1). The size of the hydrocyclones D_O, W, D_e, L_1, and L_2 was 22, 20, 5, 120, and 22 mm, respectively. The theoretical value is smaller than that of the practical value. As noted previously, the size of the hydrocyclone has to be smaller than that of the theoretical size [10,18]. The separation efficiency of the hydrocyclone system is given by:

Table 1
The purification conditions of the muddy seawater in the multicyclone system

	1st cyclone	2nd cyclone	3rd cyclone
Pressure (bar)	2	2	2
Volumetric flow rate (l/s)	1.42	1.42	0.05
Area of entrance (mm^2)	2 × 10 mm	2 × 10 mm	1.5 × 2 mm
Speed of fluid (m/s)	7.1	7.1	16.7
Cyclone dimensions (mm)	2 × 10 × Φ22	2 × 10 × Φ22	2 × 4 × Φ11

$$\eta = \sum \eta_j m_j, \eta_j = \frac{1}{1 + (d_{p50}/d_j)} \quad (4)$$

where d_j is the diameter of the particle j, η_j is the separation efficiency of the particle j, and m_j is the ratio of the mass of particle j. In our hydrocyclone system, we theoretically estimated the V_n of the first step to be about 2.9 m/s. We estimated that N_e was about 13.1 when the average mud density (ρ_P) was about 1,730 kg/m^3. The particle diameter (d_{p50}), corresponding to η of 50%, was estimated to be about 1.11 and 9.62 μm for two hydrocyclones (two different areas of the entrance as 1.5 × 2 mm and 5 × 10 mm, Blue BS Inc., Seoul National University, Suwon, Korea), respectively.

Fig. 2 shows the multihydrocyclone water pretreatment system used for the pretreatment of two muddy seawater samples, with muddy densities of 0.3556 and 0.032 kg/m^3, respectively. The disk was made of polycarbonate, and each contained 20 hydrocyclones, as shown in Fig. 2(a). The multihydrocyclone water pretreatment system consisted of three disks stacked on top of each other, as shown in Fig. 2(b). Thus, the multihydrocyclone water pretreatment system contained 60 hydrocyclones. The microbubbles were injected only into the first disc to increase the separation efficiency of the suspended solids. The aerated flocs characterization (AFC) technique was used. In the AFC method, the microbubbles cause aerated and lighter flocs to be dragged by the vortex effect into the center [16,19].

To analyze the multihydrocyclone water pretreatment system, we purified muddy seawater samples collected at Deabu Island in Korea. In the first and second hydrocyclone steps, we set the fluid flow speed of the muddy seawater samples to about 7.1 m/s at the inlet of the hydrocyclones. The speed of the muddy seawater samples was about 16.7 m/s in the third hydrocyclone step because the third step had the lowest muddy density and small particles. As COD and BOD values depend on the muddy density, we further measured the variation in COD and BOD values. After the pretreatment process, we assessed the variation in the mud density, COD, and BOD values of the seawater samples. To evaluate the muddy density, filter papers used with the muddy seawater samples and those used with clean seawater samples purified by the multihydrycyclone system were dried at 110°C for 2 h. We then compared the variation in the weight of the filter papers from the muddy seawater samples with those from the clean seawater samples. We estimated the COD value in the samples by the oxidation and reduction reaction of $Na_2C_3O_4$ and $KMnO_4$. The BOD value was obtained in milligrams of oxygen consumed per liter of sample during five days of incubation at 20°C.

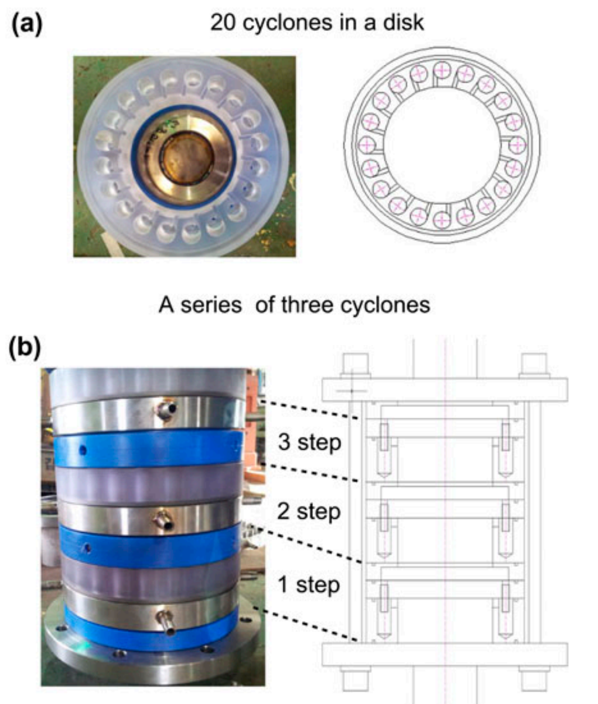

Fig. 2. The multihydrocyclone water pretreatment system used for the pretreatment of muddy seawater. (a) Horizontal section of the multihydrocyclone water pretreatment system, with 20 cyclones in a one disk and (b) vertical section of the multihydrocyclone water pretreatment system consisting of three cyclone disks.

3. Results and discussion

We used two types of hydrocyclones with two different areas of the entrance as 1.5 × 2 mm and 5 × 10 mm. The split ratio of underflow and overflow of the hydrocyclones was about 4:96. We selected an underflow rate of 4%, which is similar to that of a general pretreatment system. Increasing the rate of the underflow would likely increase the separation efficiency. The pressure of the muddy seawater in the hydrocyclone was adjustable by controlling the fluid flow speed of the muddy seawater at the inlet [8,10,18]. Fig. 3(a) shows the pressure as a function of the fluid flow speed. The pressure of the fluid linearly increased with the speed of the fluid. Thus, slightly reducing the size of the inlet at the entrance to the system increased the fluid flow to a speed suitable for smaller particles. During the pretreatment of the muddy seawater, we fixed the pressure of the seawater in the hydrocyclone to 20,000 kg/m^2 by adjusting the fluid flow speed at the entrance (Table 1). Thus, it was possible to purify 102.24 tons of muddy seawater per hour because the total volumetric flow rate of the hydrocyclone system was about 28.4 l/s. Fig. 3(b) shows the diameter distribution of the mud particles of the two muddy seawater samples, with mud densities of about 0.3556 and 0.032 kg/m^3, respectively. The particles in the 0.032 kg/m^3 muddy seawater sample were smaller than those in the 0.3556 kg/m^3 sample.

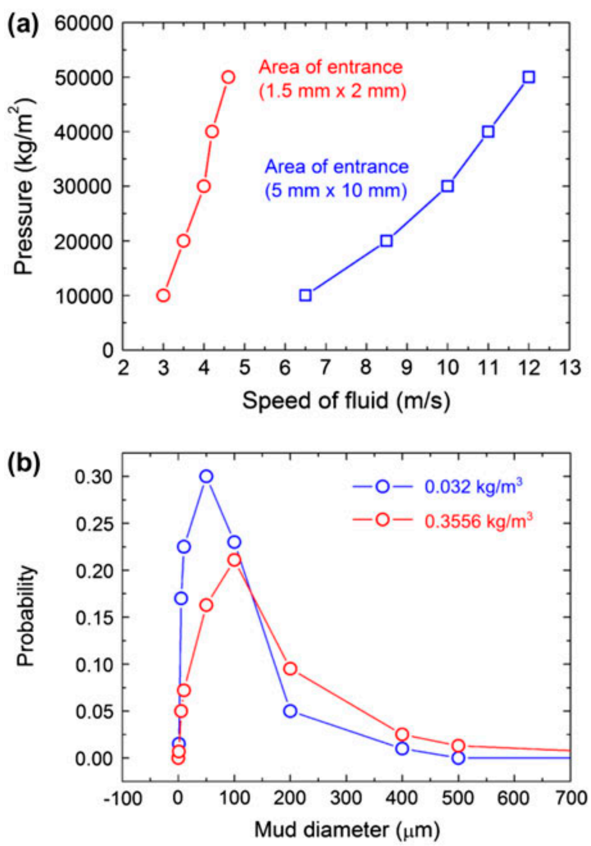

Fig. 3. (a) Pressure of wastewater in the cyclones as a function of fluid speed and (b) The mud diameter distribution of two muddy seawater samples, with mud densities of about 0.3556 and 0.032 kg/m^3, respectively.

Fig. 4 shows the results of the pretreatment of the two muddy seawater samples using the multihydrocyclone water pretreatment system consisting of three serial hydrocyclones. Table 1 shows the pretreatment conditions of the two samples, with mud densities of about 0.3556 and 0.032 kg/m^3, respectively. The hydrocyclone was designed with an underflow rate of about 4% and an overflow rate of 96%. Fig. 4(a) shows the variation curves in the mud density, COD, and BOD in the seawater as a function of the number of hydrocyclone treatment steps in the muddy seawater sample of 0.3556 kg/m^3. After the first step in hydrocyclone pretreatment process, the mud density significantly decreased (to 0.1068 kg/m^3). We confirmed that the COD and BOD in the muddy seawater samples decreased at the same time, as shown in Fig. 4(a). This decrease in the COD and BOD was due to the reduction in the mud density because mud particles adsorb, for example, organic materials, nitrites, ferrous salt, and sulfides, thereby increasing the COD and BOD [20–22]. In the second and third steps, the variation in the density of the COD and BOD remarkably decreased. We experimentally confirmed that the multihydrocyclone water pretreatment system using multiple hydrocyclone steps effectively reduced the mud density of the muddy seawater, even at a low mud density. Fig. 4(c) presents the results for the muddy seawater sample of 0.3556 kg/m^3 before the pretreatment and those for the seawater samples after the three pretreatment steps. After the first step, the muddy seawater was clearly purified. The second and third steps gradually reduced the mud density of the seawater, although the reduction in the density was lower after the first step [8,10,18]. Similar to the variation curve for the mud density, the COD and BOD in the muddy seawater asymptotically decreased with an increase in the number of hydrocyclone steps. In the multihydrocyclone water pretreatment system, the amount of mud and sewage in the seawater influenced the COD and BOD reduction.

For a comparative study, we measured the separation efficiency of the multihydrocyclone water pretreatment system of the muddy seawater sample having a mud density of 0.035 kg/m^3. Fig. 4(b) shows the mud density, COD, and BOD in the seawater as a function of the hydrocyclone step for the muddy

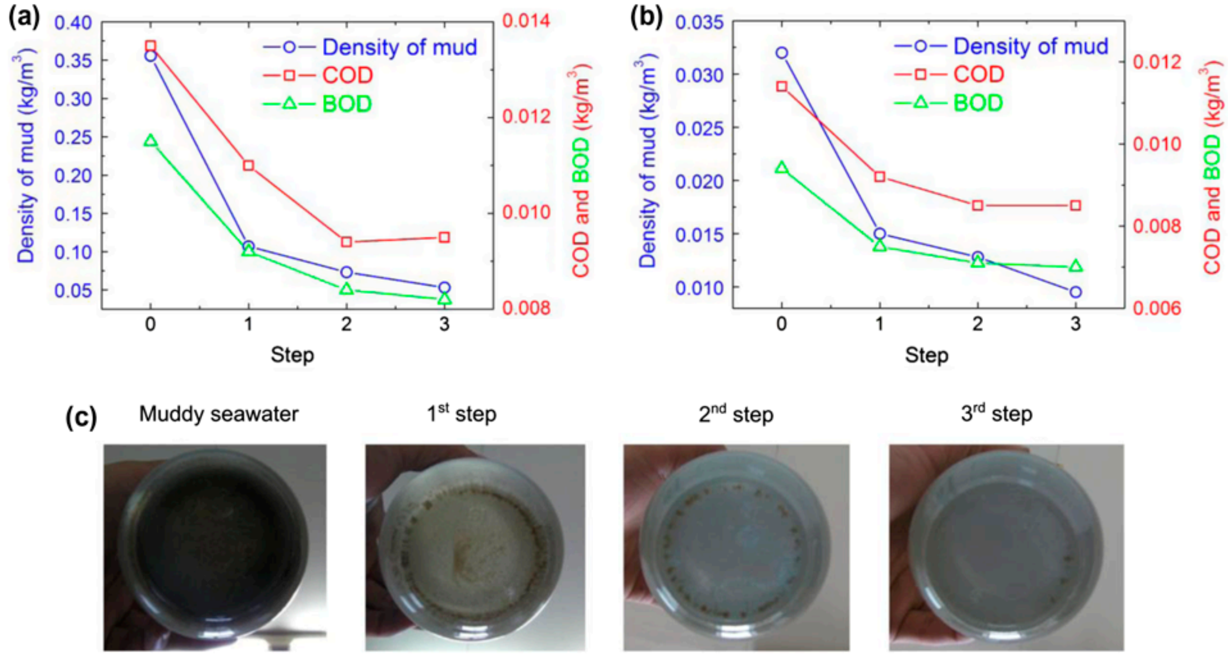

Fig. 4. (a) and (b) The variation curves of the mud density, COD, and BOD in the muddy seawater as a function of the cyclone pretreatment step in two muddy seawater samples with mud densities of about (a) $0.3556\ kg/m^3$ and (b) $0.032\ kg/m^3$, respectively. (c) Images of the muddy seawater sample with a muddy density of $0.3556\ kg/m^3$ and the purified muddy seawater samples after the first, second, and third cyclone steps.

seawater sample of $0.032\ kg/m^3$. As expected, the mud density, COD, and BOD simultaneously decreased with an increase in the number of hydrocyclone steps. The separation efficiency of the hydrocyclones asymptotically decreased in accordance with an increase in the number of hydrocyclone steps. As the separation efficiency of the hydrocyclones was close to 50%, even at a low mud density, it is inferred that a multihydrocyclone system with more than four hydrocyclones would provide cleaner water than the three-hydrocyclone system studied here in [8,9].

We further measured the separation efficiency of the multihydrocyclone water pretreatment system in a sewage sample collected at the Suwon streamlet in Korea. Fig. 5 shows the variation curves for the sludge density, COD, and BOD in the sewage sample with a sludge density of about $0.016\ kg/m^3$ as a function of the hydrocyclone step. Similar to the pretreatment results for the two muddy seawater samples, the sludge, COD, and BOD densities decreased in the sewage sample in accordance with an increase in the number of hydrocyclone steps. In the case of the sewage sample, the separation efficiency slowly decreased with an increase in the number of hydrocyclone steps. The difference in the separation efficiency is likely due to the difference in the particle density and the radius of mud and sludge particles [10,18]. We confirmed that the multihydrocyclone pretreatment system can purify muddy seawater, as well as sewage, with a uniform purification speed of about 500 ton/d.

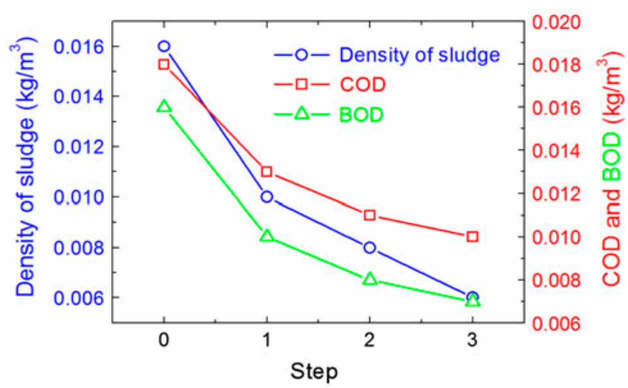

Fig. 5. The variation curves of sludge density, COD, and BOD in the sewage sample with a sludge density of about $0.016\ kg/m^3$ as a function of the cyclone step.

4. Conclusion

We used two types of hydrocyclones with different entrances of $1.5\ mm \times 2\ mm$ in the first and second steps, and $5 \times 10\ mm$ in the third step. The multihydrocyclone water pretreatment system has three hydrocyclone disks, each containing 20 hydrocyclones. In the two samples with mud densities of about 0.3556 and 0.032 kg/m^3, respectively, we examined the mud density in the seawater as function of the hydrocyclone pretreatment steps. We experimentally demonstrated that the multihydrocyclone water pretreatment process effectively reduced suspended solids, as well as the COD and BOD, in muddy seawater and sewage. Of note, the multihydrocyclone water pretreatment system is a permanent environmentally friendly water treatment system, which does not rely on any chemical processes [23].

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