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Effect of DAF configuration on the removal of phosphorus and organic matter by a pilot plant treating combined sewer overflows

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Pollutant removal by dissolved air flotation (DAF) at combined sewer overflows (CSOs) was analyzed with operating parameters such as recycling ratio and COD_{cr} concentration. The nozzle of the CO-Current DAF system is normally operated co-currently with the flocculated water. In this study, the Counter-Current DAF system was used to remove organic matter concentration and total phosphorus to prevent water pollution of river when CSOs occurred. Counter-Current flow with ejection of saturated water was studied, because the acceleration of the flow increased collisions of microbubbles with floc. The experiments showed higher removal efficiency of DAF with Counter-Current flow compared with other configurations. In addition, the direction of the DAF nozzle and variation of angle of the contact zone were studied in detail for better operation. Efficiencies were analyzed for T-P, COD_{cr}, and turbidity. The optimized conditions for DAF were a flow rate of 4.3 L/min with the Counter-Current nozzle setting. The optimum angle of contact zone was 60° rather than 45°. The removal of T-P, COD_{cr}, and turbidity at optimum conditions were shown as 82.5%, 72.9%, and 91.2%, respectively. In particular, phosphorous removal was enhanced by using the Counter-Current nozzle and by the angle of the contact zone. The removal of COD_{cr}, turbidity, T-P and SS for pilot plant showed as 75%, 82%, 80% and 92% respectively at 25 m/h of the hydraulic loading. The recycle ratio was 25%, which is considered to be an effective technique for treating CSOs.

1. Introduction

Combined sewer overflows (CSOs) usually contain sewage and rain water. In addition, they include organic and inorganic materials and suspended solids (Benotti and Brownawell, 2007; Choi et al., 2014; Seo, 2006). Most sewers are combined sewers connected with storm water. The sewage treatment plant has difficulty in operation due to the inflow of large amount of sewage over 3Q when rainfall occurs. CSOs discharged from a sewage treatment plant have to deal with high flow rate in a short retention time, therefore, the conventional technology relies mostly on sedimentation treatment. Most of the dissolved pollutants cannot be treated and discharged. CSOs are believed to be the main cause of eutrophication and algae occurrence in lakes because of their inorganic sands and variety of pollutants. CSOs commonly occur during heavy rain when they are produced in maximum quantities, so prompt measures are required (Kim et al., 2004; Sin et al., 2004). It is one of the reasons why the Ministry of Environment of Korea was interested in maintaining water quality in CSOs to prevent occurrences of water pollution (Moe, 2013). Overall, the treatment techniques encompass rapid precipitation, hydrocyclones, and dissolved air flotation (DAF). These have been applied as hybrid treatment methods combined with biological and physicochemical treatment processes (Gasperi et al., 2012; Park et al., 2011; Yin et al., 2012). The hydrocyclone has the advantage that it can separate solids from liquid at high hydraulic loading rate (Liu et al., 2015; Radman et al., 2014), while DAF can advantageously remove both particles and no precipitated material in short hydraulic retention times and operation costs are low (Edzward, 2010; Haarhoff and Edzwald, 2013; Yap et al., 2014). Table 1 shows that the removal efficiency of T-P and COD_{cr} in combination with hydrocyclone and DAF is high when using ballasted media. However, due to the low hydraulic loading rate of 15 m/h, CSOs treatment is limited (Hwang et al., 2016). The CO-Current DAF system was already developed to enhance the

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efficiency of the DAF system with forward direction of the nozzle (Crossley and Valade, 2006; Officer et al., 2001). A method of maximizing the float effect by colliding air bubbles on the floc which is the same direction of nozzle and flow. However, as air bubbles in DAF collided with flocs in the reverse direction, the results were a little short of expectation. In a DAF system consisting of contact and flotation zones, the effective floating effect determines the physical condition for the aggregating agent of the bubble-floc (Kim et al., 2015). It is believed that the DAF system requires an optimally designed contact zone shape (Bhondayi et al., 2015; Wang et al., 2015). The CO-Current DAF system is operated at a hydraulic loading rate of 5–15 m/h. DAF. It is an effective technology for handing large amount of untreated and discharged water at the short retention time. Recently, DAF with hydraulic loading rate of 30–50 m/h has appeared (Jarvis et al., 2009). In case of DAF with high hydraulic loading rate, an error in the design of the flotation zone will cause the bubble-flocs to flow out with the treated water because the hydraulic loading rate is faster than the rising velocity of bubbles. So, in order to maximize the collision effect between floc and air bubble at a high flow rate, it is necessary to develop a Counter-Current nozzle fixed in the reverser direction of the flow of water and to develop a stable DAF operating factor by changing the internal formation of the DAF. Therefore, if a structural improvement is required to operate a stable Counter-Current DAF with high hydraulic loading rate, it can be used as a more effective technique in the treatment of CSOs. In pilot plant operations, changing flow rates and flow patterns are quite limited in view of consumption time and cost. However, recently, CFD analysis has become a useful tool in understanding the relationships between laboratory tests and numerical analyses (Goula et al., 2008; Lakghomi et al., 2015; Ryu et al., 2011). The CFD analysis was used to verify the findings from laboratory tests. DAF pilot plant combined with hydrocyclone at wastewater treatment plant (WWTP) operated to reduce T-P, SS and COD_{cr} according to high hydraulic loading rate DAF operation. The purpose of this study is to determine DAF shape factors and nozzle directions related with the physical condition of the conical baffle and diffuser cone, to evaluate the treatment efficiency according to the hydraulic loading rate on DAF, to verify the effect of high hydraulic loading rate on the pilot plant based on laboratory test.

2. Materials and methods

2.1. Raw water

Raw water for lab test was prepared based on the published data of previous studies (Table 2). A carbon source was bacto-yeast extract (Difco, Michigan, USA; < 250k Daltons). It was prepared using $CH_3COONa.3H_2O$ (DAEJUNG Chemicals, Siheung, Korea). The suspended solid was kaolinite (DAEJUNG Chemicals, Siheung, Korea). The T-P was prepared using K_2HPO_4 (DAEJUNG Chemicals, Siheung, Korea) and the conditions specified were pH 7 ± 0.5 and temperature 25 ± 2 °C. The lab test was performed with several conditions to optimize nozzle, baffle and diffuser cone.

Raw water for pilot plant was used influent of Nanji WWTP in Korea (Table 3). The pilot plant was operated during rainy season to verify results of lab condition.

Table 1
Comparison of T-P and COD_{cr} removal (%) according to each unit in conventional DAF (Hwang et al., 2016).

	Hydrocyclone	DAF	Hybrid
T-P removal (%)	74.5 (sand)	84.5 (sawdust)	98.5 (sand)
COD_{cr} removal (%)	51.3 (sand)	58.0 (sawdust)	85.3 (sand)

2.2. System design

As shown in Fig. 1, an inline static mixer was first introduced to the flocculant inlet and a polymer coagulant aid was added. NaOH was used to adjust the pH. The hydrocyclone removed the precipitated heavy material. Then, untreated or unsettled particles were removed by the DAF process. In this study, to verify the effect of DAF, the whole system was evaluated in three mechanical parts: ① nozzle, ② baffle, and ③ diffuser cone. The efficiency of DAF in each setting was compared in terms of the physical shapes. The DAF pressure tank was operated at 5.5 atm and the ratio of recirculation (R_r) was fixed to 15%. The hydraulic loading rate was fixed to 5–15 m/h.

2.3. Analysis and experiment

In this study, turbidity, COD_{cr}, and T-P were measured. A turbidity meter (Hach Co. TURBIDITY, Loveland, USA) was employed to measure turbidity. COD_{cr} and T-P were analyzed using a spectrophotometer manual (Hach Co. DR 5000, USA). pH was analyzed using pH meter (Hach Co. HQ30d, Loveland, USA).

2.4. Nozzle

In the conventional approach (Nozzle (a) of Table 4), the DAF system introduces the microbubbles in co-current flow with the incoming raw water, and the DAF nozzle is in contact with the particles. The increase in efficiency was observed when DAF with a counter-current nozzle was employed. We observed that when the flow was injected in the upstream direction, collisions were evoked with air bubbles (Officer et al., 2001; Crossley and Valade, 2006). However, the change in the raw water flow from upstream to downstream seemed to reduce the flow velocity and led to a drop in collision efficiency. In this study, contrary to CO-Current DAF, the flow directed downstream (opposite to the rising direction of the microbubbles) was set to form at the contact inlet. In addition, comparisons were made with existing methods by applying the Counter-Current nozzle method as shown in nozzle (b) of Table 4, which we expected would enhance collision efficiency and the effectiveness of treatment.

2.5. Baffle

The minute bubbles in the combined bubble-effective flotation of flocs in the DAF process are larger than those in the coagulant contact zone when the separation efficiency is high. However, increasing the size of floc aggregates in the reactor seems uneconomical. Therefore, to maximize the contact area between flocs and air bubbles, creation of optimal physical shape is extremely important. The flow rate in the separation zones will influence the overall DAF process efficiency. To derive the optimum operation factors, both the shape and the height ratio of the contact zone were varied during experiments. The contact zone shape was selected between (a-1 to a-3) and (b-1 to b-3) as shown in Table 5. The contact zone height ratio (H) is defined as the ratio of processor zone height (H_b) and the DAF tank height (H_r), that is, H_b/H_r. During the experiment, the ratio was varied in the range of 65–85%.

2.6. Diffuser cone

The efficiency appears to be reduced if short-circuit currents and turbulence are formed at the upper contact and in the upflow separation zone as the hydraulic loading rate increases. Therefore,

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