Sludge disintegration using a hydrocyclone to improve biological nutrient removal and reduce excess sludge

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Abstract

Sludge disintegration can simultaneously improve biological nutrient removal and reduce excess sludge. A novel sludge disintegration method is proposed wherein a hydrocyclone is used for internal release of carbon source. The effect of hydrocyclone disintegration on mixed liquor recirculation was studied in a side-stream device of an anoxic/aerobic wastewater treatment plant (WWTP). The mechanisms of hydrocyclone disintegration were comprehensively investigated, and its energy consumption was compared with those of other disintegration methods. The sludge disintegration degree (DD) reached 6.66-12.25% in the hydrocyclone processed mixed liquor recirculation, leading to a significant increase in the concentration of soluble chemical oxygen demand (SCOD), protein and polysaccharide. However, the sludge size distribution and the stable

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structure for microorganism aggregation and cell attachment changes only slightly. The sludge disintegration process using the hydrocyclone involves sheared shedding, rotation desorption and centrifugation lysis which are mainly induced by disordered turbulence. The biological degradation experiments with continuous modes revealed significant improvements in microbial activity in disintegrated mixed liquor recirculation. Similarly, the denitrification rate of disintegrated mixed liquor recirculation was increased by approximately 15% in batch experiments. Excess sludge reduction can also be expected due to the release of organic compound from surplus sludge. Compared with other disintegration methods, hydrocyclone disintegration exhibited less intensity but lower energy consumption, which indicated that this method shows promises in advanced nitrogen removal and excess sludge reduction.

Keywords: activated sludge, hydrocyclone disintegration, carbon source, biological nutrient removal, excess sludge reduction.

1 Introduction

For the past 100 years, the activated sludge process has been the most commonly used biological process in wastewater treatment plants (WWTPs) because of its simplicity, high efficiency and low cost [1]. With the increasingly strict legislation on environmental protection and persistent pursuit of more economical operation, the long-standing problems of insufficient removal of organic matter and nutrients and the production of large amounts of excess sludge are clearly exposed [2, 3]. The potential avenues for improvement mainly focus on the utilization of novel environmental technology, such as the symbiotic interaction between tubificidae and microorganisms [4] and the investigation of filamentous bacteria for nutrient removal [5], the optimization of operational parameters such as dissolved oxygen concentration [6], and the improvement of conventional biological treatment technology [7, 8]. The typical factors that require improvement to facilitate the efficient release of the carbon source from sludge, include excess sludge and mixed liquor recirculation. An environmentally benign and economical disintegration method needed to yield total solid solubilization. Such a method would simultaneously benefit the denitrification process for total nitrogen removal and sludge digestion for reducing excess sludge [9-12].

To date, several methods have been applied for sludge disintegration, including thermal treatment [13], chemical treatment using acids or alkali [14], mechanical disintegration [10, 15, 16], biological hydrolysis [17] and a combination of the above methods [18]. Organic substances can be released from the sludge due to the desorption of loosely bound extracellular polymeric substances (EPS) and/or the breaking of the cellular plasma membrane [18]. EPS, which represent up to 50-90% of the total sludge [19], originate from the metabolism or cell lysis of microorganisms and are more valuable for disintegration [20]. Specifically, EPS are the construction material of bacterial

settlements. They either remain attached to the cell's or sludge floc's outer surface or are secreted into its growth medium. The thermal, chemical or biological disintegration treatment mainly break the protein-lipid bilayer and releases the intracellular substances [21], whereas mechanical methods comprehensively disintegrate the sludge, including EPS solubilization [22]. The development of a more economical and feasible disintegration method, such as hydrocyclone disintegration, can be significant for its ability to fully release available carbon.

As conventional separation device, the hydrocyclone consists of one or more tangential inlets, a cylinder and a conical shape. These components cause not only the known centrifugal motion of mixture [23] but also the revolution of dispersed particles on its axis [24]. Therefore, particles with a porous structure, such as sludge floc, will be improved for ad/desorption in the hydrocyclone [25]. The sludge interface will be continually updated, and the mass transfer efficiency of the cell, which is embedded in sludge, will be enhanced due to the shearing force in the hydrocyclone induced by the velocity difference between flow layers. All of these factors demonstrate the advantages of hydrocyclone disintegration over other conventional mechanical disintegration methods [26].

Based on the above characteristics, a side-stream device of an anoxic/aerobic WWTP was setup for sludge disintegration by a hydrocyclone. Such a device is typically designed for separation. Because of the close correlation between sludge microbial activity and disintegration degree (DD), as reported by Li H. et al. and Schlafer O. et al. [27, 28], the sludge in the mixed liquor recirculation was chosen as the disintegrate target. Our new attempt of disintegrating the mixed liquor recirculation is also more convenient to the improvement of WWTP rather than excess sludge. The main objective of this study was to investigate the effects of hydrocyclone disintegration of sludge in the mixed liquor recirculation, conducted with different hydrocyclone pressure drop (ΔP , defined as energy

consumption) values on organic compound release, DD, the particle size distribution from sludge and microorganism activity. The mechanisms of hydrocyclone disintegration were explored based on the measurement and simulation of the hydrocyclone flow field. In our experiments, we also monitored the effect of hydrocyclone disintegration on the biological process and quantitatively compared the economic efficiency of operation. This latter analysis helps instruct application.

2 Materials and methods

2.1 Experiments

The hydrocyclone disintegration apparatus was built as the side-stream device of the 60t/h East China University of Science and Technology (ECUST) WWTP located in Shanghai, China. This WWTP operates using the conventional anoxic/aerobic process and mainly accepts the campus sewage. Only a small portion of the sludge was disintegrated in the mixed liquor recirculation because of the instantaneous disintegration process. The sludge typically flows back to the anoxic tank to participate in the biodegradation process. The hydrocyclone disintegration process will be appropriately adjusted to ensure the stabilization of mixed liquor suspended solids (MLSS) and to avoid the production of excess sludge. The energy consumption of the hydrocyclone is sufficiently low that no additional facility is needed for the disintegration of sludge in the mixed liquor recirculation. Instead, the use of the existing return pump is sufficient. In the future improvement of a subsequent full-scale plant, the sludge in the mixed liquor recirculation is more feasibly used as the substrate for disintegration rather than the surplus sludge from the hydrocyclone disintegration process.

2.2 Disintegration methods

2.2.1 Hydrocyclone-disintegration apparatus

The ECUST anoxic/aerobic WWTP consists of an anoxic tank, an aerobic tank, a secondary sedimentation tank and pump units. During the return from the aerobic tank to the anoxic tank at the ratio of 300%, a small amount of the internal flow was fed into the hydrocyclone from the bypass pipes. The hydrocyclone-processed mixed liquor recirculation was disintegrated and mainly discharged to the anoxic tank from the hydrocyclone underflow. Only 5% of the effluent was discharged as overflow to maintain the stability of the swirling flow and the removal of some excess dissolved oxygen. A schematic of sludge disintegration system using a hydrocyclone is shown in Fig. 1.

Fig. 1. Schematic of sludge disintegration using a hydrocyclone in anoxic/aerobic process.

2.2.2 Hydrocyclone

The hydrocyclone used for sludge disintegration is shown in Fig. 2, and the structural parameters of the optimized design are listed in Table 1. The hydrocyclone is made of polyurethane and has a typical single-tangential inlet and single cone. The single cone is also widely used for separation. In our experiments, the hydrocyclone ΔP is always less than the return pump's outlet pressure of 0.25 MPa. This pressure also represents the hydrocyclone disintegration strength for solubilization carbon release. Four sets of hydrocyclone operation parameters are listed in Table 2 to investigate the effect of disintegration intensity on disintegration efficiency.

Fig. 2. Structure and photograph of the hydrocyclone.

Table 1 Geometric parameters of the hydrocyclone

$D(\text{mm})$	θ	W/D	H/D	D_o/D	D_d/D	L/D
100	8	0.35	0.10	0.12	0.30	1.5

Note: W and H are the width and height of the feeding tube; D , D_o , and D_d refer to the diameters of the swirl chamber, overflow tube, and underflow tube, respectively.

Table 2 Operation parameters of the hydrocyclone

No.	Flow rate	Pressure drop
	m^3/h	MPa
I	10.44	0.07
II	11.69	0.10
III	12.63	0.13
IV	13.17	0.16

2.3 Sludge and wastewater characteristics

The influent fed to the hydrocyclone was collected from the aerobic tank. The specific characteristics of the domestic wastewater were as follows: pH of 7.52 ± 0.29 , chemical oxygen demand (COD) of

162.7 ± 31.3 mg/L, soluble COD (SCOD) of 113.8 ± 15.9 mg/L, total nitrogen (TN) of 25.3 ± 5.4 mg/L, ammonia nitrogen (NH₄-N) of 21.8 ± 4.1 mg/L, and nitrate nitrogen (NO₃-N) of 0.31 ± 0.17 mg/L. The MLSS concentration used in the experiment was 4566 ± 372 mg/L. These wastewater and sludge characteristics are averages based on dozens of measurement results. During the anoxic/aerobic operation, the dissolved oxygen concentration in the aerobic tank was controlled at 4-6 mg/L, and the surplus sludge return ratio was set at 50%. In addition, the COD, NH₄-N and suspended solids (SS) in the effluent was less than 25, 2 and 10mg/L, respectively, which meets the local discharge standards.

2.4 Analytical methods

Comprehensive measurements were performed in accordance with the standard methods from the American Public Health Association for, SS, MLSS, COD, TN, NH₄-N and NO₃-N [29]. The dissolved oxygen (DO) concentration in wastewater was measured by portable dissolved oxygen sensors (OxyGuard, Denmark). Particle size analysis was carried out using a Laser Particle Size Analyzer (Beckman Coulter, US) [30]. For each analysis, the mixture sample was pre-treated by 0.4 W/mL ultrasound for 15 s to prevent sludge coalescence resulting from sampling to measurement. The specific input energy in ultrasonic pretreatment and retention time was optimized according to dozens of contrast tests. Protein was quantified by Lowry's method with bovine serum albumin as the respective standard [31]. Carbohydrate was quantified by the anthrone-sulfuric acid method with glucose as the respective standard [32]. The dehydrogenase activity was determined by the improved triphenyl tetrazolium chloride method [33]. Protease was measured as described by Kavitha et al. [34]. The sludge disintegration degree was calculated as the ratio of the increase in SCOD by sonication to the maximum possible SCOD increase:

$$DD_{\text{COD}} = (\text{SCOD} - \text{SCOD}_0)/(\text{TCOD} - \text{SCOD}_0),$$

where SCOD and SCOD₀ are the SCOD values for the disintegrated and untreated samples, respectively, and TCOD is the total COD [35]. The disintegrated mixed liquor recirculation from hydrocyclone underflow was quickly removed and digested in laboratory-scale 12 L anaerobic reactors to measure the denitrification rate. This rate is calculated as the rate of decrease in the total nitrogen concentration. All experiments were conducted in triplicate.

3 Results and discussion

3.1 Sludge disintegration

3.1.1 Organic compound release

The effect of hydrocyclone disintegration on organic compound release was investigated at the stable stage of anoxic/aerobic operation. Fig. 3(a) shows the changes of SCOD, and Fig. 3(b) shows the changes in DD. The relationship between sludge disintegration and hydrocyclone ΔP was also evaluated in terms of the release of soluble carbon release. As previously reported [12], a significant increase in soluble COD was observed along with the increase in hydrocyclone ΔP , which corresponds well with other mechanical disintegration processes [10]. On five different points with a regular time interval, the SCOD concentration in the disintegrated mixed liquor recirculation increased by $162.31 \pm 56.25\%$ to 298.5 ± 50.1 mg/L, whereas DD increased by 6.66-13.65%. However, the growth rate of SCOD markedly decreased to zero after ΔP increased to 0.2 MPa. The SCOD increase by hydrocyclone disintegration is far less than that by other mechanical disintegration methods [22].

Fig. 3. Effect of hydrocyclone disintegration on organic compound release.

Sludge disintegration experiments was performed to synchronously investigate the effect of the hydrocyclone ΔP on the concentration changes of protein and polysaccharide in the mixed liquor recirculation, as presented in Fig. 4. Protein increased by $10.51 \pm 9.85\%$ to $144.61 \pm 21.67 \text{ mg/L}$, whereas the polysaccharide increased by $22.81 \pm 14.99\%$ to $8.69 \pm 1.16 \text{ mg/L}$. Furthermore, the amounts of protein and polysaccharide increased with increasing hydrocyclone ΔP , essentially in agreement with SCOD. The carbon resource in sewage was enhanced because of release of sludge organic substances from extracellular and intercellular components. This release benefits biodegradation and nutrient removal. The influence of the disintegration strength on the ratio of extracellular polysaccharides to proteins was also verified for the hydrocyclone. A higher

hydrocyclone ΔP resulted in a higher ratio of extracellular polysaccharides to proteins, which is in accordance with the results of Qin et al. [36].

Fig. 4. Effect of hydrocyclone disintegration on protein and polysaccharide release

3.1.2 Sludge size distribution

The results of the particle size distribution for all disintegrated sludge showed that the hydrocyclone disintegration process was unrelated to the sludge size (Fig. 5). The median size of the raw sludge in the mixed liquor recirculation was approximately 26.1 μm , whereas the variation ratio range of disintegrated sludge was approximately 5%. All the size distributions of sludge are highly similar. Additional experiments showed that the size distribution of disintegrated sludge barely changed only

slightly with the further increases in hydrocyclone ΔP . This result is in disagreement with other mechanical disintegration treatments [30, 37]. The main reason for the lack of change in the sludge size is likely that the hydrocyclone process is transient and the amount of sludge being disintegrated is small.

Fig. 5. Sludge size distribution

Activated sludge floc is composed of a large amount of water, EPS and microorganisms. The microorganisms, include bacterial colonies, filamentous bacteria and single bacteria. The sludge floc functions as the attachment structure for the microorganisms. Therefore, the size distribution of sludge is related to its surrounding environment and may affect its dewatering. During organic compound release, negligible changes in sludge size indicated that the structural integrity of the disintegrated sludge was largely retained after being processed by the hydrocyclone. The disintegrated sludge also avoids the breakage on the microbial attachment carriers and the destruction on biological activity. The activated sludge in the processed mixed liquor recirculation most likely did not become looser, excluding the negative effect on biomass flocculation and sludge sedimentation.

3.2 Mechanisms of hydrocyclone disintegration

Because of the existence of disordered turbulence in the hydrocyclone that led to sludge collision, fragmentation and agglomeration, the mechanism of hydrocyclone disintegration is complex compared with other sludge disintegration treatments. The hydrocyclone disintegration process involves sheared shedding, rotation desorption and centrifugation lysis, as determined by simulations and measurements.

3.2.1 Sheared shedding of hydrocyclone disintegration

As is well known of the tangential velocity, the hydrocyclone continuous phase is a nonuniform flow, which results in the appearance of a tangential velocity difference between fluid elements. The tangential velocity gradient gives rise to a proportionate shear force [38], leading to collisions and grinding between activated sludge floc. The continuously secreted metabolin, known mainly as EPS gradually fills the sludge porous channel or even covers the surface of the activated sludge. The frequent collision or grinding of the sludge likely disrupts the adherence of EPS, leading to the sheared shedding. Sludge external metabolin, especially the LB-EPS from organic matter released from the flocs, led to a significant increase in the SCOD concentration in the mixed liquor recirculation. Sludge disintegration mainly occurred in the boundary layer or near the air core in the hydrocyclone because of the large shear force.

3.2.2 Rotation desorption of hydrocyclone disintegration

Dr He F. [39] built a 3D high-speed camera system and investigated the movement of dispersed particles in terms of the trajectory and velocity distribution at a frequency of 5080 fps. Several anisotropic core-shell microparticles of a similar size to sludge were used to simulate the sludge in the hydrocyclone. The microparticle location and rotation will be recognized from both the front view and vertical view. The simulated microparticle revolving about its own axis was verified and

widely observed in the hydrocyclone. The rotation of sludge benefits sludge disintegration and, in particular, the desorption of the EPS matrix of the porous inner sludge. The released organic matter also results in an increased SCOD concentration in the aqueous phase of the sludge. In addition, the appropriate desorption of EPS likely improves the mass transfer of sewage and enhances the removal of organic compound and nutrients.

3.2.3 Centrifugation lysis of hydrocyclone disintegration

The influent from a single tangential inlet flows downward in the hydrocyclone and maintains centrifugal movement because of the constraint of the conical part of the hydrocyclone. The centrifugal separation factor of the sludge peaks as it moves to the side wall [40]. Meanwhile, the intracellular substances of cells likely pass through the plasma membrane (a protein-lipid bilayer that forms a barrier separating cell contents). The cell lysis in the hydrocyclone will release the cell contents into the medium, providing an inherent substrate that contributes to the organic loading and microbial metabolism. Unlike the sheared shedding or the rotation desorption process of hydrocyclone disintegration, the centrifugation lysis disintegration refers to cell death induced by breaking the cellular membrane, destroying the biological process. Once lysed in the hydrocyclone, those neighboring living cells will biodegrade the lysed cells, and an increase in lysis efficiency can lead to an overall reduction in sludge production.

3.3 Effect of hydrocyclone disintegration on the biological process

3.3.1 Enzyme activities

Proteins and polysaccharides are the major organic components in the EPS. These compounds must be hydrolyzed to smaller units by enzymes in subsequent biodegradation. Therefore, enzymes play essential roles in organic matter removal and sludge reduction of biological processes. As the basis

of protein hydrolysis, protease is highly correlated with sludge digestion. Dehydrogenase (DHA) is an enzyme belonging to the group of oxidoreductases that can oxidize certain substrates. The microbial energy and metabolism of organic matter are programmed to the DHA reduction reaction that transfers one or more hydrides (H-) to an electron acceptor. In our experiments, the disintegrated mixed liquor recirculation by the hydrocyclone, operating at pressure drop of 0.13 MPa, was removed into the 5 L anoxic/aerobic reactor for continuous digestion. The protease and DHA of the disintegrated sludge were regularly sampled and compared with those of normal sludge, as shown in Figure 6. As the degradation process continues, the enzyme activity of both disintegrated and normal sludge increases to the maximum and then slowly decreases to a constant. The variation trends of protease activity and DHA activity are nearly identical, as are their time to reach the maximum. However, the maximum protease and DHA activities of disintegrated sludge are significantly greater than those of normal sludge. The maximum protease and DHA activities of disintegrated sludge are 31.32% and 29.24% higher than those of normal sludge, respectively. The subsequent enzyme activity has a larger decline, and the minimum disintegrated sludge is lower.

During the initial degradation, the enzyme activities were improved by hydrocyclone disintegration because the unsteady turbulent flow in the hydrocyclone accelerated the secretion of extracellular enzymes. Furthermore, the rotation desorption in the hydrocyclone dredged the mass transfer channel of organic substrates and nutrients, improving biodegradation. Later, during degradation, the nutrient substances degraded thoroughly as disintegrated sludge rather than as normal sludge. The enzyme activities had a larger decline and finally became lower. The hydrocyclone disintegration, which benefits enzyme activities indirectly, indicated its potential beneficial effect on organic matter removal and sludge reduction.

Fig. 6. Protease and DHA activity

3.3.2 Denitrification rate

Nitrate removal was characterized with respect to degradation time in batch experiments. Both disintegrated and normal sludge were simultaneously sampled at four random time points. Fig. 7 shows the time course of the denitrification rate at a hydrocyclone ΔP of 0.13 MPa. In the first 60 min, anaerobic digestion in the batch reactor proceeded successfully because of the inherent abundance of the carbon source. The disintegrated sludge was fractionally further ahead, presumably due to the enhanced enzyme activity. Along with the progressive consumption until depletion of the inherent carbon source in the next 60 min, a more significant decrease in the denitrification rate was

observed in the normal sludge. Nevertheless, the disintegrated sludge maintained nearly steady denitrification because of the additional carbon source from disintegration until the depletion of nitrate. Finally, the total nitrogen removal by disintegrated sludge reached 97.1% rather than 82.7% for normal sludge. Moreover, the released carbon source, particularly volatile fatty acids (VFAs), is anaerobically taken up and supplied as an electron donor. The specific ratio of carbon to nutrients such as phosphorus or nitrogen indicated the suitability of the wastewater for biological treatment. Then, the accumulation of nitrite occurred due to the insufficient carbon source resulting from consumption via denitrification. The supplementary carbon source increased the anaerobic denitrification of the disintegrated sludge in the mixed liquor recirculation considerably due to hydrocyclone disintegration.

Fig. 7. Denitrification rate

3.4 Economic analysis of hydrocyclone disintegration

The feasibility of this novel hydrocyclone disintegration method is closely associated to its practicality. The method's prospects depend on the amount of carbon source release, the change in enzyme activities, nutrient removal and excess sludge reduction. Those disintegration methods differ in terms of energy consumption and the suitability of the machines for practical application, which considerably influences technology selection. Müller J. A. [41] focused on mechanical disintegration and compared its results to those of thermal and ozone treatment using the specific energy. Specific energy is defined as the amount of mechanical energy that stresses a certain amount of sludge. In

Figure 8, the novel hydrocyclone disintegration approach was compared with that of Müller. Both the disintegration degree and specific energy of the hydrocyclone are less than those for the other treatment methods. Although hydrocyclone disintegration reached nearly 25% of the other disintegration methods at a medium degree of disintegration, its energy consumption was less than 12% of those of the other methods, including only 1% of the ultrasonic homogenizer. In the practical application of the activated sludge process, the ratio of mixed liquor recirculation typically ranged from 200% to 400%. As such, more carbon source will be produced due to the circulation caused by hydrocyclone disintegration. Hydrocyclone disintegration is more economic according to the final evaluation of the cost effectiveness analysis.

Fig. 8. Specific energy as a function of DD for various disintegration methods

4 Conclusions

- 1) The conventional activated sludge in the mixed liquor recirculation is partially disintegrated by the hydrocyclone. SCOD, protein and polysaccharide increased with increasing hydrocyclone ΔP until reaching a steady state. The sludge size distribution changed only slightly because of the transient hydrocyclone disintegration process.

- 2) Sheared shedding, rotating desorption and centrifugation lysis induced by disordered turbulence in the hydrocyclone are the main reasons for sludge disintegration.
- 3) The enhancement of enzyme activities after hydrocyclone disintegration, as exhibited by the denitrification rate, indicated the potential for hydrocyclone disintegration to improve nitrogen removal and excess sludge reduction.
- 4) Hydrocyclone disintegration is more economical and has lower energy consumption than other sludge disintegration methods based on an evaluation of DD. This observation means this method has extensive prospects in industrial applications.

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Sheared Shedding

Rotation Desorption

Centrifugation Lysis

Release of Carbon Source & Enhancement of Microbial Activity

Improved Nutrient Removal

Excess Sludge Reduction