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Optimization of Energy Consumption of the Ultrasonic Pretreatment on Sludge Disintegration

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Abstract. Anaerobic digestion is a widely used method to treat sludge, while its application was limited by its ineffective hydrolysis rate. Ultrasonic pretreatment could enhance the hydrolysis rate of sludge, while the development of ultrasonic had been restricted by the high energy consumption, it was necessary to optimize the energy consumption. Disintegration degree was analysed by the particle size, SCOD increase, soluble proteins and carbohydrates of the sludge before the after the ultrasonic pretreatment, the relationship between the specific energy input and the disintegration degree was discussed. The results showed that after ultrasonic disintegration, the concentration of SCOD, soluble protein and carbohydrate increased with the increase of ultrasonic time and ultrasonic power. High power ultrasonic could effectively disintegrate sludge in a short disintegration time, while low power ultrasonic needed a long time to disintegrate sludge. And under the same specific energy consumption conditions, the combination of lower power density and longer ultrasonic time could obtain better disintegration degree than the combination of higher power density and shorter time. It was confirmed that the energy utilization efficiency of the lower power density and the longer time combination was higher.

1. Introduction

With the accelerating progress of urbanization, the scale and quantity of urban sewage treatment plants are also increasing, and the sludge production from of sewage treatment plants is also increasing [1]. The excess sludge composition is complex, mainly including various organic matter, heavy metals and pathogenic microorganisms. If the sludge is carelessly disposed, the sludge will have extremely adverse effects on the environment. At present, there are various treatment and disposal methods for excess sludge, including landfill, incineration, anaerobic digestion, composting, etc. Among these methods, anaerobic digestion technology can make the sludge resource, reduce, stabilize and harmless treatment, which is an effective way to solve the sludge pollution problem. [2].

Due to the problems of low digestion efficiency, low gas production, long reaction period and large floor space during anaerobic digestion of sludge, the application and promotion of the process are greatly limited. The main reason for this problem is that the slow hydrolysis rate of sludge, and the hydrolysis of sludge has been considered as the rate-limiting step in anaerobic digestion [3, 4]. Pretreatment of the sludge prior to anaerobic digestion releases the organic matter, which accelerates the rate of anaerobic digestion. Commonly used pretreatment methods include thermal hydrolysis [5], ultrasonic [6], alkaline hydrolysis [4] and the like. Among them, the ultrasonic technology has fast reaction efficiency, high degree of disintegration and no secondary pollution, which is one of the commonly used pretreatment techniques.

However, due to the high energy consumption of ultrasonic technology, it is often necessary to optimize the input energy and sludge disintegration degree, which can obtain optimal energy utilization. High-power ultrasonic can effectively disintegrate the sludge in a short time, while low-power ultrasonic need much longer time to disintegrate sludge effectively. In practical applications, how to optimize the balance of ultrasonic energy input and sludge disintegration degree is an urgent problem to be solved.

In this study, ultrasonic technology was used to pretreat sludge with a solid concentration of 3%, the changes of physical and chemical properties of sludge under different ultrasonic power intensities were studied, and the balance between the energy input of ultrasonic waves and the degree of sludge disintegration was analyzed, which provided data support for engineering applications and operations.

2. Experimental materials and methods

2.1. Sludge materials

The sludge used in the test was the excess sludge from a sewage treatment plant in Tianjin. A^2/O activated sludge treatment process was used in this plant with a treatment capacity of 300,000 m^3/d. After the sludge was taken back, it was naturally settled, and the supernatant was removed. The bottom sludge was left to be used, and the sludge solid concentration was about 3%.

2.2. Experimental equipment and instruments

The probe type ultrasonic reactor was shown in Figure 1. The reactor was mainly composed of an ultrasonic transducer, an ultrasonic probe, a soundproof box and an ultrasonic generator. The ultrasonic frequency was 20 kHz and the power could be adjustable from 120 to 1200 W. When the reactor was used to disintegrate the sludge, the quantitative sludge was taken up in a 1 L beaker and placed in a soundproof box. The probe was immersed 1-2 cm in the surface of the sludge liquid, and the disintegration time was freely regulated.

Figure 1. Ultrasonic horn reactor

2.3. Pretreatment methods

The sludge to be treated was taken out from the refrigerator to room temperature, diluted with TS to 8% with deionized water, and stirred well. 800 mL of the mixture was put into a 1 L beaker at a time, and 120 W, 480 W, 720 W, 960 W, and 1200 W power were used at a frequency of 20 KHz, then the sludge was ultrasonically cracked at the power density of 0.15 W/mL, 0.6 W/mL, 0.8 W/mL, 1.2 W/mL and 1.5 W/mL, respectively. A total of six disintegration times were set at each power density: 10 min, 15 min, 20 min, 30 min, 45 min, and 60 min.

2.4. *Test items and methods*

The determining method of the conventional indicators of sludge in this study was shown in Table 1. Unless otherwise specified, the indicators were determined by the standard method recommended by the American Public Health Association [7].

Table 1. Detection methods and equipments

Parameters	methods	Test instrument
TS、VS	Weight	Sartorius BS124S
TCOD、SCOD	Potassium dichromate	HACH DRB200
NH_4^+-N	Nessler's reagent	HACH DR2800

(1) Carbohydrates

Soluble Carbohydrate: Determined by the anthrone colorimetric method [8].

Total Carbohydrate: Dilute the sludge mixture and sample under agitation, as determined by the above method [9].

(2) Protein

Soluble protein: determined by the Lowry method [10].

Total protein: After dilution with the sludge mixture, the sample was stirred under the above conditions as determined by the above method [9].

(3) Sludge particle size

The sludge particle size distribution and average particle size were determined using a Malvern laser particle size analyzer (MasterSizer 2000, Malvern, UK).

3. Results and discussion

3.1. *Change in mean particle size of sludge*

When the sludge was ultrasonically cracked, the disintegration degree of the sludge can be analyzed by observing the change of the average particle size of the solid particles in the sludge. The change of average particle size with time at different power densities was shown in Figure 2. As can be seen from the figure, as the ultrasonic time increased, the sludge particle size gradually decreased. At the beginning 15 min of ultrasonic disintegration, the sludge particle size decreased rapidly, and the particle size reduction rate became slow after 15 min. When the disintegration time was 30 min and the ultrasonic power density was 0.15 W/mL, 0.6 W/mL, 0.9 W/mL, 1.2 W/mL and 1.5 W/mL, the average particle size of the sludge was 39.784 μm, 35.134 μm, 30.882 μm, 20.082 μm and 18.131 μm, respectively. When the power density increased from 1.2 W/mL to 1.5 W/mL, the sludge particle size changed limitedly. Excessive ultrasonic power had limited help on disintegration the particle size. At each power, the first 15 min disintegration time was the fastest to reduce the particle size of the sludge. After 15 minutes, the speed was slowed down. It was confirmed that the disintegration time within 15 min was most effective for disintegration the sludge particles, and with the ultrasonic time increased, the speed of disintegration the particle size gradually slowed down.

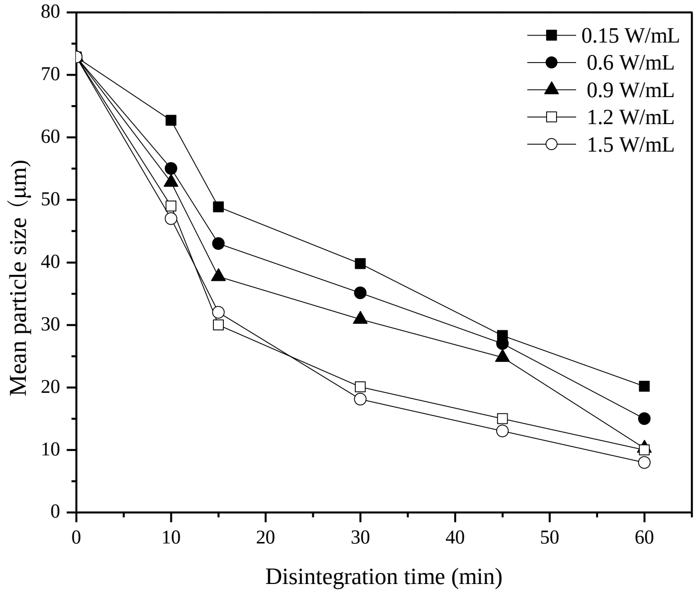

Figure 2. Mean particle size of sludge after ultrasonic pretreatment

The results showed that the increase of ultrasonic power and disintegration time had a significant effect on reducing the particle size of the sludge, and it was confirmed that the degree of disintegration was proportional to the ultrasonic input energy, but the excessive ultrasonic energy consumption was also not conducive to the reduction of the particle size. The disintegration time of 15 min was most effective for sludge particle disintegration, and the disintegration efficiency was gradually reduced with the extension of time.

3.2. *COD disintegration*

Figure 3 showed the variation of SCOD with the disintegration time after 2% TS sludge disintegration under different power density ultrasonic conditions.

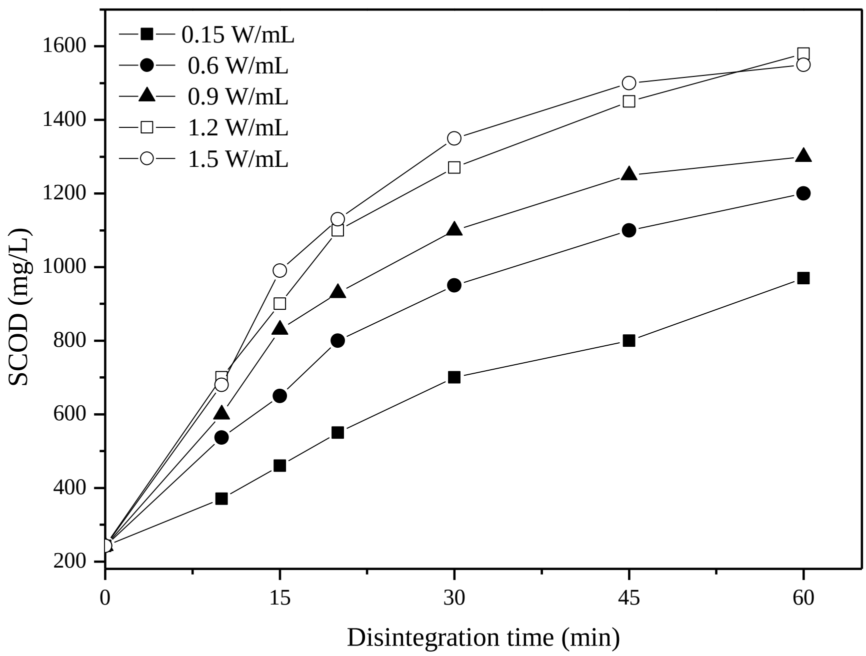

Figure 3. SCOD concentration of sludge after ultrasonic pretreatment

In this test, the initial SCOD of the sludge was 242 mg/L, and the concentration of SCOD gradually increased with the increase of ultrasonic power density and ultrasonic time. When the ultrasonic power was 30 min at the ultrasonic power density was 0.15 W/mL, 0.6 W/mL, 0.9 W/mL, 1.2 W/mL and 1.5 W/mL, the SCOD values increased to 700 mg/L and 900 mg/L, 1100 mg/L, 1270 mg/L and 1350 mg/L, respectively. After 30 min, as the time continued to increase, the SCOD increment at the ultrasonic power density of 0.6 W/mL, 0.9 W/mL, 1.2 W/mL and 1.5 W/mL was gradually gentle, but the SCOD value continued to increase at the power density of 0.15 W/mL. At the same time, as the ultrasonic power density increased, the SCOD gradually increased, but the increment gradually decreased. When the ultrasonic power density were 1.2 W/mL and 1.5 W/mL, after 20 min ultrasonic pretreatment, the SCOD values were 1100 mg/L and 1130 mg/L, respectively.

The above results showed that when the power was high, the disintegration efficiency was higher in a shorter time, and further disintegration time was helpless to disintegration. When the power was low, the disintegration efficiency was always low, but the disintegration time can be maintained, extending the crack time could help crack the efficiency. Chu et al [11] studied the disintegration effect of low-power ultrasound on sludge, and the results showed that low-power ultrasound (0.33 W/mL, 20 min) had a significant effect on the floc structure disintegration of the sludge, and greatly improved the amount of methane produced after anaerobic digestion. Liu et al. [12] studied the effect of low-power ultrasound on the biodegradability of sludge, and summarized the influence of different parameters on the disintegration effect of the sludge, namely ultrasonic treatment time>power density>acoustic intensity, when the power is low, it often took a long time to achieve a better disintegration effect, and however, when the high-power ultrasonic cracked the sludge, the disintegration was finished in a short time. Grönroos et al. [13] found that high-power ultrasound can achieve better disintegration effect in a short time, continued extension of time would cause waste of ultrasonic energy, and the degree of disintegration was not obvious. Show et al. [14] pointed out in the study that when high-power ultrasound cracked sludge, cavitation could be completed in a short period of time, so the ultrasonic intensity could be increased to shorten the water retention time to save energy.

Therefore, under different power conditions, the impact of disintegration time on the disintegration effect is different, and comprehensive analysis of different disintegration power and disintegration time is needed. Studying the relationship between the energy consumption parameters and the degree of disintegration is of great significance for the energy saving and the improvement of the degree of disintegration.

3.3. *Effect on dissolved proteins in sludge*

The organic components in the excess sludge mainly include proteins, polysaccharides and lipids. Most of the organic components are encapsulated by microbial cells and extracellular polymers in the sludge. After the ultrasonic pretreatment, the SCOD increased, which mainly due to the dissolution of protein, and the polysaccharides [1].

Figure 4 was the effect of dissolved protein concentration on disintegration time at different power density ultrasonic pretreatments. It could be seen from the figure that as the disintegration time increased, the concentration of dissolved protein in the sludge after ultrasonic pretreatment at different power densities gradually increased. Under each power condition, the concentration of dissolved protein in the sludge increased linearly with time in the first 20 min. When the disintegration time was 20 min, the dissolved protein concentrations at the power densities of 0.15 W/mL, 0.6 W/mL, 0.9 W/mL, 1.2 W/mL, and 1.5 W/mL were 280 mg/L and 400 mg/L, 530 mg/L, 621 mg/L and 643 mg/L, respectively. It showed that at the same time, the protein was more dissolved at a higher power density, and the degree of sludge disintegration was higher. It showed that the disintegration efficiency was higher under the power density of 0.9 W/mL, 1.2 W/mL and 1.5 W/mL within the first 20 min. The concentration of soluble protein at 0.15 W/mL and 0.6 W/mL power density always increased linearly with time. The results showed that the protein concentration increased with the increase of ultrasonic time and ultrasonic power, and the effective disintegration time was shorter under high power conditions, while

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the effective disintegration time was longer under low power conditions, which was consistent with the COD study results in the previous section.

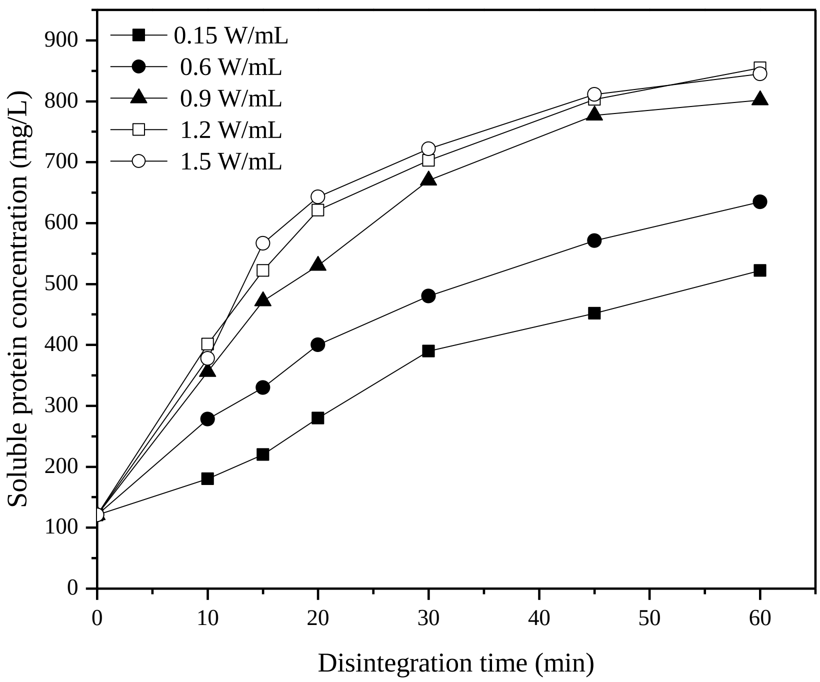

Figure 4. Soluble protein concentration of sludge after ultrasonic pretreatment

After the sludge was disintegrated, the proteins located in the extracellular polymer and intracellular of the sludge microbial were released into the liquid phase. After the protein was hydrolyzed in the liquid phase, ammonia nitrogen was produced to increase the ammonia nitrogen concentration [15, 16]. It was more convenient to evaluate the dissolution of the protein by analyzing the concentration of ammonia nitrogen in the sludge.

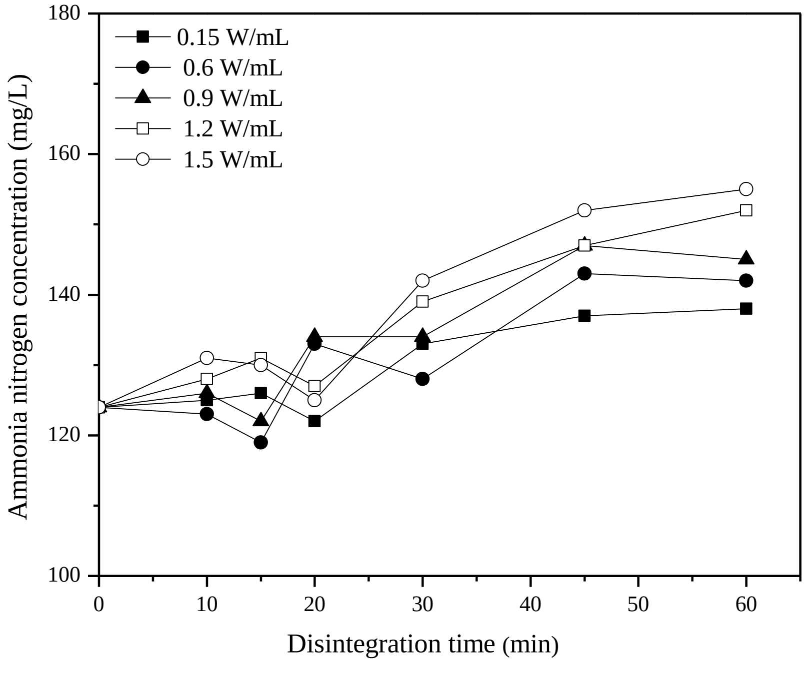

Figure 5. NH_3-N concentration of sludge after ultrasonic pretreatment

The ammonia nitrogen concentration in the ultrasonic pretreated sludge at different power densities was shown in Figure 5. It can be seen from the figure that with the extension of the ultrasonic disintegration time, the concentration of ammonia nitrogen in the sludge increased slightly at each power density, indicating that some proteins were hydrolyzed as the concentration of dissolved protein increased. After 60 min ultrasonic decimation, the concentrations of ammonia nitrogen at the power densities of 0.15 W/mL, 0.6 W/mL, 0.9 W/mL, 1.2 W/mL, and 1.5 W/mL were 138 mg/L, 142 mg/L, and 145 mg/L, 152 mg/L and 155 mg/L respectively. The ammonia nitrogen concentration at each power density was not much different, and the increase was smaller than that in the untreated, indicating that although the concentration of dissolved protein was increasing in the 60 min disintegration time, only a few proteins were hydrolyzed.

3.4. *Effect on dissolved carbohydrates in sludge*

Figure 6 showed the concentration of dissolved polysaccharide in the sludge with the ultrasonic disintegration time under the ultrasonic power density. As shown in the figure, as the ultrasonic time increased, the concentration of dissolved polysaccharides in the sludge also gradually increased. When the disintegration time was 20 min, the concentrations of the soluble polysaccharides at the power densities of 0.15 W/mL, 0.6 W/mL, 0.9 W/mL, 1.2 W/mL, and 1.5 W/mL were 233 mg/L and 321 mg/L, 401 mg/L, 433 mg/L and 441 mg/L respectively. The results showed that higher power densities could dissolve more polysaccharides. At the same time, similar to the dissolution of protein, the concentration of polysaccharide increased linearly with time before 20 min, and the concentration of polysaccharide increased after 20 min. When the disintegration time was 60 min, the concentrations of the soluble polysaccharides at the power densities of 0.15 W/mL, 0.6 W/mL, 0.9 W/mL, 1.2 W/mL, and 1.5 W/mL were 321 mg/L, 412 mg/L, 517 mg/L, 534 mg/L and 545 mg/L, respectively. The results showed that the increase in power could increase the concentration of polysaccharides, but too high power had limited help for polysaccharide dissolution. Therefore, the appropriate power density and disintegration time should be selected according to the specific disintegration situation. Excessive disintegration power and excessive disintegration time were easy to cause energy waste. If energy utilization efficiency was considered, the power density and the disintegration time should be matched according to the specific energy consumption parameters of the ultrasonic wave, and then the optimal combination of power density and crack time was preferred.

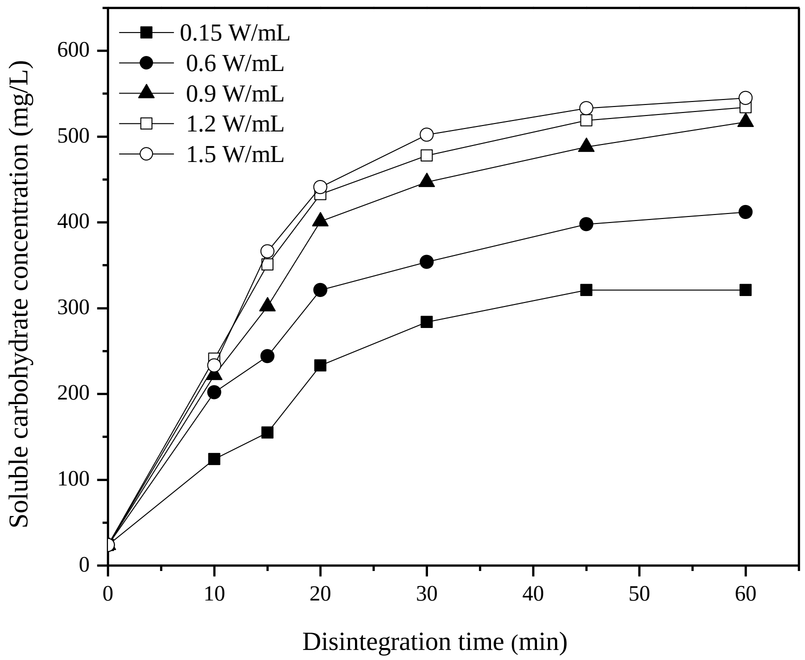

Figure 6. Soluble carbohydrate concentration of sludge after ultrasonic pretreatment

3.5. *Relationship between specific energy consumption and sludge disintegration degree*

The relationship between different ultrasonic power density and duration of action and sludge SCOD concentration was shown in Table 2. It could be seen from the table that as the specific energy consumption increased, the concentration of SCOD also increased gradually. When the specific energy consumption was 133746.4 kJ/kg-TS, the maximum SCOD value of 1270 mg/L could be obtained. Under the same specific energy consumption, the combination of different power density and ultrasonic time would result in different SCOD concentration values. When the specific energy consumption was 16718.3 kJ/kg-TS, the maximum SCOD was 700 mg/L. When the specific energy consumption was 33436.6 kJ/kg-TS, the maximum SCOD is 970 mg/L, at this time, the power density was 0.15 W/mL, and the ultrasonic time was 60 min. When the power density is 66873.2 kJ/kg-TS, the maximum SCOD value was 950 mg/L, and the power density and ultrasonic time were 0.6 W/mL and 30 min, respectively. Therefore, under the same specific energy consumption conditions, the optimal SCOD values were the combination of lower power density and longer ultrasonic time, and the higher power density and the SCOD value in the shorter time were relatively lower.

Table 2. Relationship between ultrasonic power density, duration and SCOD concentration under the same specific energy consumption

Specific energy consumption （kJ/kg-TS）	Power density×duration （W/mL× min）	SCOD （mg/L）
16718.3	0.15×30	700
	0.6×7.5	460
	0.9×5	425
	1.2×3.75	400
	1.5×3	400
33436.6	0.15×60	970
	0.6×15	650
	0.9×10	600
	1.2×7.5	575
	1.5×6	575

66873.2	0.6×30	950
	0.9×20	930
	1.2×15	900
	1.5×12	810
133746.4	0.6×60	1200
	0.9×40	1190
	1.2×30	1270
	1.5×24	1220

The above results showed that the SCOD concentration in the lower power density and longer time combinations was higher than the higher power density and shorter time combination at the same specific energy consumption, indicating a higher power utilization efficiency for lower power density and longer disintegration time combinations. Therefore, under the premise of improving energy efficiency, lower power density and longer time should be preferred.

4. Conclusion

(1) The increase of ultrasonic power and disintegration time had a significant effect on reducing the particle size of the sludge, confirming that the degree of disintegration was proportional to the ultrasonic input energy, but the excessive ultrasonic energy consumption was also not conducive to the reduction of the particle size. The disintegration time of 15 min was most effective for sludge particle disintegration, and the disintegration efficiency was gradually reduced with the further increase after 15 min.

(2) The concentration of COD, protein and polysaccharide increased with the increase of ultrasonic time and ultrasonic power. Under the high power condition, the sludge could be effectively disintegrated in a short disintegration time. While under the low power, it needed a longer time to disintegrate the sludge.

(3) Under the same specific energy consumption conditions, the optimal SCOD value was obtained under a combination of lower power density and longer ultrasonic time. The energy utilization efficiency of the lower power density and longer time combination was higher than the combination of high power density and short time.

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