Influence of Microwave and Ultrasonic on Sludge Dewaterability by Numerical Simulation of Horizontal Spiral Sedimentation Centrifuge

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Abstract. Microwave and ultrasonic are used as pretreatment technologies of sludge, because of the excellent performance on improving sludge dewaterability. This study focuses on viscosity and particle size of sludge to study by numerical simulation. The results show that the Settle Volume (SV), viscosity, and the moisture content of the sludge reduced. The increase in the Chemical Oxygen Demand (COD) concentration also indicates a significant disruption of complex floc structures. The particle size of sludge ranged from 33.55μm to 28.98μm, 9.44μm of microwave and ultrasonic pretreatment. Three-dimensional flow field in the centrifuge on the dewatering efficiency of structural parameters and sludge pretreatment are investigated numerically by using Computation Fluid Dynamics (CFD) software FLUENT. The results show that improvement of separation efficiency can be achieved by not only increasing the length-diameter ratio, but also decreasing the sludge viscosity.

Keywords: sludge, microwave, ultrasonic, dewaterability, numerical simulation

1 Introduction

Sludge dewatering is significant because it is economically and environmentally friendly to the minerals, chemicals and water treatment industries. Disposal of sludge is costly; however, the reduction of sludge volumes through dewatering can provide large cost savings [1-3]. Because of the large quantities of water, biomass and Extracellular Polymeric Substance (EPS), sludge is difficult to be dewatered by normal method. For material properties, subsequent dewatering process and equipment will be greatly influenced by sludge pretreatment which is a preliminary treatment process for sludge thickening & dewatering and can mainly be realized by chemical methods, heating, elutriating, freezing and adding skeletal particles and so on [4]. New pretreatment technologies involve ultrasonic, microwave, pyrohydrolysis, magnetic field, electroosmosis and biological flocculants, etc [5-8]. Capillary Suction Time (CST), viscosity, Settle Volume (SV), moisture content, Chemical Oxygen Demand (COD), zeta potential and morphology of sludge adopted to test dewaterability [9-14].

Raf Dewila [15] reported the extensive investigations using an ultrasonic treatment of wasted activate sludge, and studied its potential to reduce sludge quantities and achieved a better dewaterability. In the study of Chu [16] after 2-4 min treatment of ultrasonic under intensity of 400 W m^{-2}, the bound water of the sludge decreased from 16.7 g g-1 (dry base) to above 2.0 g g^{-1}. Tian [17] inspected the change of the sludge setting, the filtering dewaterability in 130s microwave radiation sludge pretreatment and explored the related mechanism through the particles size distribution and the content of sludge EPS change.

Horizontal spiral sedimentation centrifuge is extensively used in industries regarding petroleum, building and chemical engineering, which effectively separates the solid from the liquid by taking advantages of density differences between solid and liquid phases as well as comparatively greater centrifugal action. Jens Schmidt [18] explored the influences of the changes in structural parameters on the internal flow field of centrifuge during micro-scale centrifugal separation. Zheng [19] simulated the internal flow field of a centrifuge by Computation Fluid Dynamics (CFD) software, and analyzed the factors influencing the separation of a centrifuge. Jan Margraf [20] adopted CFD calculations for the pure liquid flow reveal that the Coriolis force induces a strong tangential flow relative to the rotating vessel. Marcus [21] used numerical (CFD) and semi-analytical techniques in the simulation of an eccentric tube centrifugal oil pumping system for hermetic compressors.

This research aimed at the excellent performance on improving sludge dewaterability by conditioning technologies (microwave and ultrasonic). Firstly, dewaterability of sludge was characterized by CST, viscosity, SV, moisture content, COD, zeta potential and particle size distribution in the experiment. Then the numerical simulation of horizontal spiral sedimentation centrifuge was adopted to examine the influence of sludge conditioning technologies on the sludge dewaterability.

2 Materials and Methods

In this section, in order to study the effect of sludge conditioning technologies (microwave and ultrasonic), the experiment was designed to estimate the dewaterability of the sludge by some parameters.

2.1 Materials

The sludge was sampled from waste water treatment facility at Huangcun plant of Beijing Drainage Corporation. The pH value (6.85) of and the moisture content (99.32%) of the original sludge is measured by water content test instrument of MA 100 infrared moisture meter with accuracy of 0.1 mg.

2.2 Method

There are lots of sludge characterization methods were showed in many references such as CST, SV, COD, particle size distribution, etc [22-24], in our research we chose some representative parameters which reflected the dewaterability of the sludge to study. The flow chart of the total experiment was shown in Fig. 1.The experiment used ultrasonic and microwave to pretreat the sludge firstly, and then, representative parameters were tested, including CST, viscosity, SV, water content, COD, Zeta potential and particle size distribution. Finally a model was established to predict the moisture content. The experiment equipment was listed in the Table 1.

MD-6 microwave sample treatment system is adopted. The parameters are as follows: temperature control range: 0 to 300°C, temperature control accuracy: ± 0.5°C; direct contact pressure measurement, real-time monitoring of 900 psi; controlling pressure accuracy: 0.01MPa; exhaust volume 3 m^3 min^{-1}. Ten samples were processed at the same time. Sonics Materials 750 ultrasonic processor is adopted. The parameters are as follows: ENERGE: 50000 J; the ultrasonic amplitude AMPL: 35%.

Table 1. Experiment equipment list

Test	Type	Manufacturer
Microwave treatment sys-	MD6	Beijing Michem Instrumentation Co.,
Ultrasonic processor	Sonics Materials 750	Sonics & Materials, Inc.
Viscosity	RV1	HAAKE
Particle size	Malvern Mastersizer 2000	Malvern Instruments Ltd
CST	Triton Electronics Type 319 Mul-	Triton Electronics Ltd
Moisture content	MA100	Sartorius

The CST static filtration test measures the filtration rate in terms of time for free water to pass between two electrodes using a filter paper as the medium. It is used primarily to indicate filter cake permeability[25, 26].

Because of the EPS and the material inside the cells transformed to soluble substances, soluble protein, carbohydrate, lipid and volatile organic acids increased, resulting in sludge COD changed[27, 28].

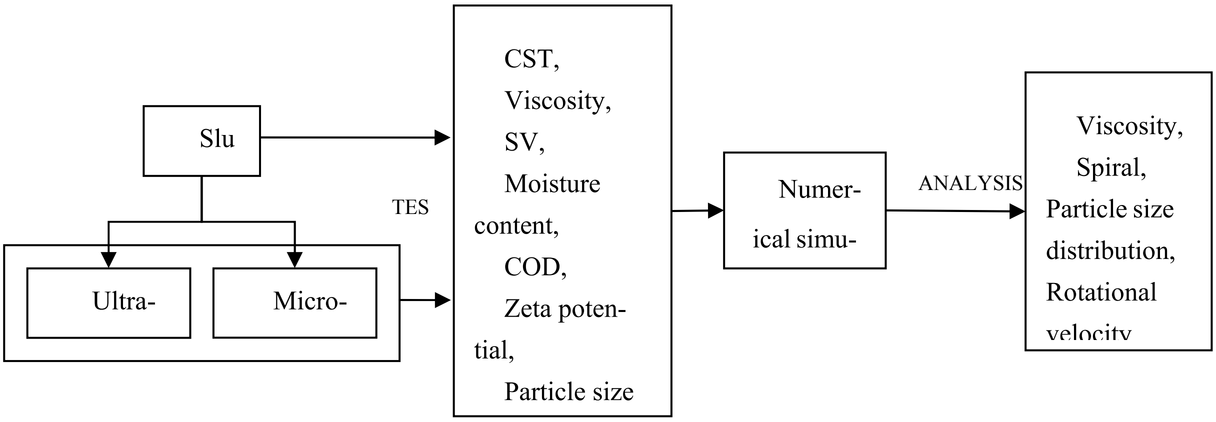


Fig .1. The flow chart of the total experiment.

Viscosity was selected to characterize the of the sludge because the sludge was transformed into a more fluid sludge mass after the pretreatment and the viscosity of sludge exhibited positive changes[29]. The viscosity of the sludge was estimated by using HAAKE RV1 rheological tester. Its main technical parameters are as follows: torque range: 0.1-50 mN m, rotational speed range: 0.15-1000 min-1. The supernatant of pretreatment sludge after the centrifugation is tested by potassium dichromate method to characterize the organic matter release.

Particle size is measured by laser diffraction technique, where the sludge (without supernatant fluid) is used as the sample, and water is used as dispersion mediator. Particle size distribution before and after the pretreatment are compared to observe sludge particle distribution during the range of easy dehydration[30]. Malvern Mastersizer 2000 particle size analyzer is adopted and its accuracy is higher than 1% (polydisperse standard) and size range is 0.02-2000 μm. Electronic microscope (Olympus CX41) and CCD (Charge-coupled Device, JVC) were used to observe slice image after different pretreatment (microwave and ultrasonic) to evaluate dewaterability. Fractal dimension is analyzed for the images of sludge to characterize the morphological parameters and aggregation state changes of sludge floc.

Fully-enclosed and continuous horizontal spiral sedimentation centrifuge has been widely used in the world as main equipment of sludge dewatering. It has several advantages such as automatic control, fully enclosed operation, etc, and guarantee low energy consumption, small drug consumption, easy operation and low operating cost during the processing of sludge treatment[31]. Due to the complexity of the nature of the sludge, experimental study is necessary to solve and determine the optimal design parameters and operation parameters before the production or design. Experimental study has certain limitations, so adopt Computation Fluid Dynamics (CFD) to simulate[32].

CFD are widely used in many fields such as turbo air classifier [33, 34], water process tanks [35] and centrifuge. The horizontal spiral centrifuge with experimental data from previous step was simulated using CFD. In a horizontal spiral centrifuge, the solid bowl and spiral conveyor rotate at different speed, so as to separate suspension and discharge sediment. In the simulation, the liquid density was 1015 kg m^{-3} and the liquid viscosity was 0.001003 Pa s. The inlet of feed pipe was selected as velocity of 0.5 m s^{-1}. The outlet of the horizontal spiral centrifuge was used for outflow, which was determined from outflow boundary condition. The outer wall of solid bowl was designated as no-slip boundary condition of rigid wall. As for the wall on the free surface, the shearing force was set as 0. The velocity of rotation angle was determined as 30-50 rad s^{-1} and the rotation difference was assumed as 2-5 rad s^{-1} for the solid bowl of the designated horizontal spiral centrifuge. To simulate the movement of the solid particles, Discrete Phase Model was adopted, while a slip model was used when a spiral conveyor was considered.

3 Results and Discussion

In this section, some results of the experiment and the simulation were concluded by several figures and tables, and it was clearly achieved that the best condition of sludge pretreatment technologies.

3.1 Microwave pretreatment

The sludge was pretreated by microwave system under different temperature conditions. The temperature was achieved to 50°C, 60°C, 70°C, 80°C, under 15°C min^{-1} heating rate. The sludge dewatering characteristics include SV, viscosity, moisture content, CST and Zeta potential (as shown in Table 2).

Table 2. Dewatering characteristics after microwave

T (°C)	SV (%)	CST (s)	Viscosity (mPa s)	COD (mg L^{-1})	Zeta potential (mV)	Moisture content (%)
20	40	36.9	12.880	290	-3.42	87.24
50	40	38.3	13.982	400	-3.20	86.60
60	31.25	40.9	14.836	429	-3.23	85.55
70	28.57	36.00	11.270	480	-2.86	83.12
80	23.33	37.83	12.938	576	-2.26	83.21

A high-frequency microwave heating causes the accelerated motion and collision of the charged sludge particles, and promotes sludge structure destabilization. Simultaneously, the microwave causes the temperature binding ability between the bound water and the EPS, thereby improving the dewaterability of the sludge. The corresponding reduction in SV, viscosity and moisture content can be seen from Table 2. The variation of CST and Zeta potential is obvious. Solubility COD is a vital parameter to estimate the dewaterability of the sludge after pretreatment. The supernatant COD content in the sludge after centrifugation is gradually increased, which indicates that microwave pretreatment technique achieve a better dewaterability, provokes a release of COD from solid, preferably transforms into biodegradable organics and possibly destroys EPS of sludge. On the contrary, the excessive microwave energy deteriorates the dehydration effect of sludge.

3.2 Ultrasonic pretreatment

The sludge was pretreated by ultrasonic under 0s, 20s, 40s, 60s, 80s. The results of dewaterability of sludge were shown in Table 3.

Table 3. Dewaterability after ultrasonic

T (s)	SV (%)	CST (s)	Viscosity (mPa s)	COD (mg L^{-1})	Zeta potential (mV)	Moisture content (%)
0	40	32.1	10.756	296	-3.42	90.51
10	27.5	182.5	5.803	762	-3.40	91.05
20	25	180	5.616	925.6	-2.89	89.40
40	20	198.5	5.276	1562.4	-3.00	89.33
60	12.5	178.2	5.224	1984	-2.20	86.85
80	15	215.4	5.308	2130	-2.21	86.98

Ultrasonic cavitation caused tremendous hydraulic shear, which broke the EPS in the sludge system, thereby undermining powerful molecular force between original flocs. It can be seen from Table 3 that the SV, viscosity, moisture content reduced accordingly. CST and Zeta potential were not changed significantly, and COD content was gradually increased. However, adversely the follow-up treatment of sewage has excessively high COD content. Excessive ultrasonic energy will deteriorate sludge dewatering effect.

3.3 Particle size distribution

The particle size distribution after 50°C, 60°C, 70°C, 80°C microwave heating was measured, and the corresponding data was recorded in Table 4.

Table 4. Particle size after microwave

T (°C)	20	50	60	70	80
Particle size (μm)	33.55	28.06	28.93	28.98	29.21

The average particle size of the sludge is 33.55 μm without microwave pretreatment; however, the particle size is reduced significantly after microwave. The size of the sludge increased gradually with the increase of the temperature. It can be conclude that microwave can change the internal structure and the nature of the sludge. With the increase of the temperature of the microwave heating, the sludge particle size increased gradually, which indicated that the thermal effects of microwave increased molecular motion and collisions among sludge particles. Therefore, small particles aggregated into larger particles.

The sludge after 0s, 10s, 20s, 40s, 60s, 80s ultrasonic is selected as the sample. The average particle size of the sludge was measured, and the data is recorded in Table 5.

Table 5. Particle size after ultrasonic

T (s)	0	10	20	40	60	80
Particle size (μm)	33.55	12.63	10.47	9.73	9.68	9.44

It can be seen from Table 5 that the particle size of the sludge is gradually reduced with increasing ultrasonic time. The particle size of the sludge is 33.55 μm without ultrasonic treatment; however, the smallest particle size can be achieved to 9.44 μm after ultrasonic treatment. With the increase of the time of ultrasonic, the sludge granularity tends to be stabilized.

3.4 The correlativity of moisture content and dewaterability parameters

According to the experimental data analyzed the correlativity of moisture content and dewaterability parameters and recorded in Table 6 and Table 7.

Table 6. The correlation coefficient of moisture content and dewaterability parameters after microwave

T (°C)	SV (%)	CST (s)	Viscosity (mPa s)	COD (mg L^{-1})	Zeta potential (mV)
-0.194	0.206	-0.857	-0.637	-0.064	0.199
0.52	0.48	0.57	0.69	0.56	0.50

Combined with the analysis of the above data in Table 6, the greater influence on the moisture content of sludge is CST, Viscosity, microwave temperature, etc.

From the calculation result of the gray associate degree coefficient of dewaterability parameters and moisture content, it is found that the largest coefficient of viscosity and moisture content is 0.69, followed by CST.

Table 7. The correlation coefficient of moisture content and dewaterability parameters after ultrasonic

Time (s)	SV (%)	CST (s)	Viscosity (mPa s)	COD (mg L^{-1})	Zeta potential (mV)
-0.934	0.839	-0.476	0.491	-0.909	-0.991
0.52	0.62	0.60	0.70	0.55	0.63

Combined with the analysis of the above data in Table 7, the greater influence on the moisture content of sludge is ultrasonic time, Zeta potential, SV, etc.

From the results of the gray associate degree coefficient of dewaterability parameters and moisture content, it is found that the largest coefficient of viscosity and moisture content is 0.70, followed by Zeta potential.

3.5 Simulation

Horizontal spiral sedimentation was simulated in combination with the sludge condition and modification (microwave and ultrasonic) to analyze the impacts of suspension viscosity and particle size distribution on the separation efficiency.

The viscosity of the suspension is primarily dependent upon the viscosity of liquid phase and concentration of suspension. After theoretical analysis and simulation, the impacts of the viscosity on the separation efficiency of a centrifuge can be reflected. At present, there have been multiple conditioning technologies available for apparently reducing the viscosity of sludge. It will be favorable for the solid-liquid separation once the sludge viscosity is reduced. In this case, the sludge dewatering efficiency is improved, so the pretreatment of the sludge is an indispensable part. In this paper, the sludge viscosity measured by conditioning properties of sludge was simulated to analyze the impacts of conditioning technologies on the sludge dewatering efficiency.

To examine the effects of the viscosity on the separation efficiency, the solid-liquid separation of a horizontal spiral centrifuge was simulated by Discrete Phase Model (DPM) according to microwave conditioning results under the situation that the length-diameter ratio changed. The simulation parameters are: the rotation speed of solid bowl was 50 rad s^{-1} and inlet velocity was 0.5 m s^{-1}. DPM solves Navier-Stokes equations in a Eulerian frame for continuous phase and solves trajectories of particles in a Lagrangian frame for discrete phase that makes the single particle as the object. Trajectory is calculated by integrating the particle force balance equation in a Lagrangian frame:

$$\frac{du_P}{dt} = F_D(u - u_P) + \frac{g_x(\rho_P - \rho)}{\rho_P} + F_x$$

In the above equation, $F_D = \frac{18\mu}{\rho_p D_P^2}\frac{C_D \mathrm{Re}}{24}$, u is the velocity of continuous phase, u_P is the velocity of particle, μ is the molecular viscous coefficient of fluid, ρ and ρ_P are the density of fluid and particle, D_P is particle diameter, C_D is drag coefficient, and Re is the relative Reynolds number. F_x, additional forces, is caused by pressure gradient, thermophoretic, rotating reference frame, Brownian motion, Saffman lift and other.

Length-diameter ratios and the length of the cylindrical section of the solid bowl show in Table 8. After simulation, the separation efficiency under the different operating conditions is shown in Table 9 as follows.

Table 8. Different length-diameter ratios carry with corresponding length of the cylindrical section of the solid bowl

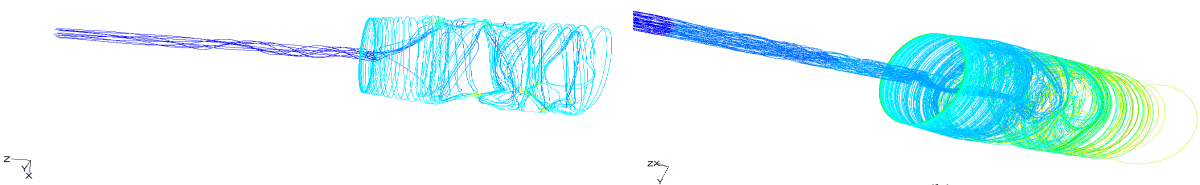
Length-diameter ratio	2.5	3	3.5	4
The length of the cylindrical section of the solid bowl (mm)	615	825	1035	1245

Table 9. Influence of viscosity upon the separation efficiency when length-diameter ratio changed (unit: %)

Viscosity (mPa s)	2.5	3	3.5	4
11.270	89.63	91.04	93.41	96.45
12.880	89.57	91.11	93.41	96.41
12.938	90.03	91.05	93.17	96.52
13.982	89.94	89.88	93.89	96.31
14.836	89.23	90.13	93.78	96.27

From Table 8 and Table 9, it can be seen that the separation efficiency of a centrifuge would be improved or weakened as the viscosity increased. This is because there were only small changes in viscosity and the turbulence inside the flow field was obviously changed under the action of spiral. This was incoherent with the theories about laminar flow. However, the separation efficiency improved with the increase of length-diameter ratio when the viscosity remained unchanged, which revealed that the centrifuge of high length-diameter ratio was good for solid-liquid separation. The separation efficiency was apparently improved when there was spiral, as the driving force of spiral was favorable for impelling particles to move towards the cone section of centrifuge. In addition, spirals could also block some solid particles that flew back. All of these facilitated the effective separation of solid and liquid phases.

Particle size distribution is one of the major factors affecting the solid-liquid separation. When the volume percentage is the same, the dewatering efficiency differs to certain extent for the sludge where different sizes of particles are distributed. To examine the optimum particle size distribution for solid-liquid separation and guide sludge conditioning, the motion trajectories of solid particles of different sizes were simulated with and without spiral. Under the situation when the length-diameter ratio is determined as 4 and inlet velocity is 0.5m s^{-1}, different separation efficiency is obtained for different solid-phase particles distributed in suspension at different rotational speed. Fig. 2(a) shows the motion trajectory of particles (the diameter of which was 80 μm) when there was no spiral, while Fig. 2(b) was the motion trajectory of particles when the spiral existed. As shown in Fig. 3, the separation efficiency of materials with different particle size at different rotational speed of solid bowl was clearly presented.



(a) (b)

Fig. 2. Particle motion trajectory. (a) Motion trajectory of 80 μm particles with no spiral; (b) Motion trajectory of particles when spiral existed.

It is obvious in Fig. 2 that the motion trajectory of particles is more concentrated and close to inerratic helical motion when spiral exist than spiral don't exist, and the concentrated and inerratic helical motion trajectory is beneficial t separation, so the spiral promotes the separation efficiency.

As shown in Fig. 3, the separation efficiency was improved as the solid bowl rotated at an increasingly higher speed. In the mean time, the large particles were in suspension, the higher efficient the separation was. This is because larger centrifugal force would act upon particles when the rotational speed was higher and particle size was larger, which would be more favorable for solid-liquid separation. When there was no spiral and most particles were small, the separation efficiency could be rapidly improved by increasing the rotational velocity. Nonetheless, centrifugal sludge separation got more efficiency when there was spiral. Thus, it can be seen that the spiral is effective for centrifugal sludge separation, whereas the effect isn't so remarkable with the increase of rotational speed. Thus, it can be concluded that spiral has great impacts upon the separation efficiency and most effects are positive. As shown in Table 4 and Table 5, the average particle size of the sludge was approximate to 30 μm after microwave treatment, and it was about 10 μm after ultrasonic treatment. In combination with the data as shown in Fig. 3, it can be seen in this experiment that the sludge after microwave treatment was more conducive to dewatering than the sludge after ultrasonic treatment with regard to particle size.

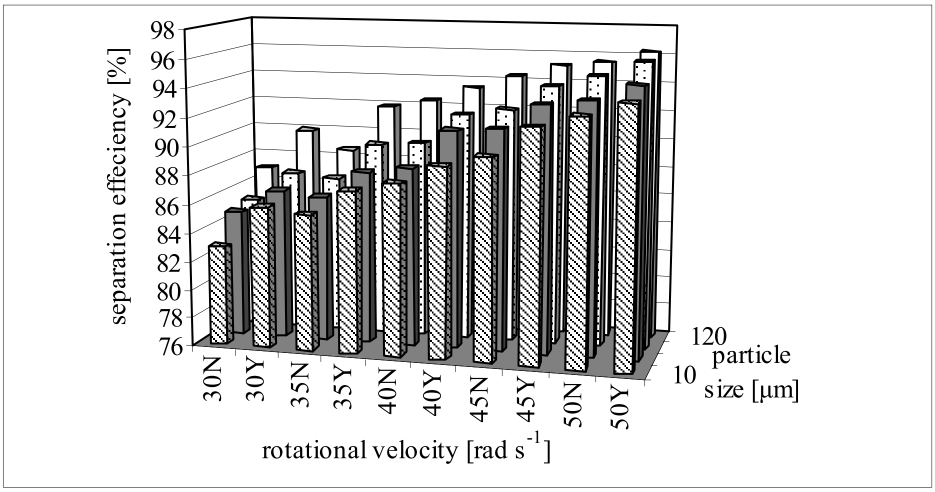


Fig. 3. The separation efficiency of materials with different particle size at different rotational velocity. 30N: 30 rad s^{-1} without spiral; 30Y: 30 rad s^{-1} with spiral. The rest can be done in the same manner.

4 Conclusion

The treatment and disposal of sewage sludge is one of the most problematical issues affecting wastewater treatment in the word. Sewage sludge treatment is an important step in sewage treatment, dewatering is a necessary process of sludge treatment and resource. By microwave and ultrasonic radiation cause the accelerated motion and collision of the charged sludge particles, and promotes sludge structure destabilization.

Appropriate microwave and ultrasonic radiation are conducive to improve the dewaterability of sludge. When the radiation energy is too high, the sludge dewatering effect will deteriorate. The experiment shows that SV, viscosity, and moisture content of sludge are reduced, and the supernatant COD content increased with increasing radiation energy. It can be found that viscosity and moisture content have the largest coefficient through calculating the gray associate degree coefficient. But in this numerical simulation, the separation effect has been influenced but not greatly by viscosity because it is relatively lower without great changes.

The morphological characteristics of the sludge changes significantly. After microwave modification, the particle size of the sludge ranges from 33.5 μm to 28.98 μm. The microscopic image analysis shows that the particle of the sludge became coarse. After ultrasonic modification, the particle size of the sludge ranges from 33.55 μm to 9.44 μm. The size of sludge particles changes obviously and more particles distribute at easily dehydrated section of 10~30 μm ·

The dewatering efficiency of horizontal decanter centrifuge is significantly influenced by structural and operating parameters, as well as material properties, which is improved as the solid bowl rotated at an increasingly higher speed. In the same speed, the larger particles are in suspension, the more efficient the separation is, from the numerical simulation. The spiral is effective for centrifugal separation, and sludge after microwave treatment was more conducive to dewatering with regard to particle size.

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