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Insight into the sludge reduction performances by hydrodynamic cavitation

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ABSTRACT

Insight into the sludge reduction performances by hydrodynamic cavitation (HC) were investigated. Mixed liquor suspended sludge (MLSS) and mixed liquor volatile suspended solids (MLVSS) decreased first and then increased as the increase of HC time from 0 to 240 min, and the lowest MLSS was 756.86 mg/L at 120 min. HC treatment promoted the increase in the solute chemical oxygen demand (sCOD) concentration and disintegration degree (DD_{sCOD}) of sludge, and the values of sCOD and DD_{sCOD} at 240 min were 319.66 mg/L and 22.98 %, respectively. The particle sizes at the 10th percentile (d(0.1)), the 50th percentile (d(0.5)) and the 90th percentile (d(0.9)) in particle size distributions decreased from 8.97, 21.10 and 49.10 μm to 0.04, 4.45 and 26.90 μm, respectively. The protein concentration in tightly bound extracellular polymers (TB-EPS) reduced with the increasing HC time from 0 to 240 min, while that in loosely bound EPS (LB-EPS) decreased firstly (during 0–120 min) and then gradually increased (during 120–240 min). As the increase of HC time, tryptophan protein in LB-EPS at 120 min and tyrosine protein in TB-EPS at 240 min disappeared in 3D excitation–emission matrix spectra.

1. Introduction

Activated sludge is widely applied in wastewaters treatments, while most sludge have not been properly treated [1,2]. Sludge usually contains many poisonous materials such as refractory organics and pathogens, suggesting that the disorderly discharge from untreated sludge will lead to many environmental problems [3–5]. As a result, it is essential to achieve the sludge reduction. Sludge reduction depends on the destruction of cell walls [5,6]. To break cell walls efficiently, many treatment methods have been studied including thermal hydrolysis, high-pressure homogenizer, ultrasonic, microwave, alkaline and oxidation treatment [7,8]. However, accustomed methods are generally characterized as more by-products or long time and low capacity of treatment [9,10].

Hydrodynamic cavitation (HC) effect occurs when liquid flows through the throttling devices (such as venturis or nozzle plate) [11]. The restrictor action will increase the kinetic velocity and reduce the pressure as the liquid passes through the restriction [12,13]. When the partial pressure is lowers than the critical pressure (saturation steam stress), liquids rapidly evaporate along with the creation of millions of cavities, and these cavities will become cavitation bubbles. Subsequently, the pressure recovers as the liquid jet expands, causing the cavitation bubbles to collapse. The collapse of cavitation bubbles results in the generation of powerful shock waves, high-velocity jets (400 km/h), high temperatures (5000–10,000 K) and high stresses (50-100 MPa) [11–13]. These extreme conditions, which are caused by the collapse of cavitation bubbles, contribute to water pyrolysis, forming hydroxyl radicals and hydrogen radicals [14,15]. The collaboration of physical and chemical effects can effectively rupture cell walls and organic matters [16,17]. Lee et al. [18] studied the impacts of HC on the sludge disintegration degree, and found that HC produced the decrease of sludge disintegration degree. Jung et al. [11] found that HC treatment could decrease the sludge particle size. Mancuso et al. [1] found that HC system could increase the solubilization and biodegradability of sludge. These investigations have proven that HC could significantly change sludge properties, which provides a potential novel way for sludge disposals. Therefore, it is necessary to explore the limitation of HC in the sludge reduction field for promoting its potential application development. However, previous studies mainly focused on the effect of HC on sludge particle size, disintegration degree and biodegradability etc., and little information has been pursued to assess the limit of sludge amount reduction by HC.

The work main purposes were (i) to evaluate the effects of HC on sludge reduction; (ii) to assess the changes in the organic matters

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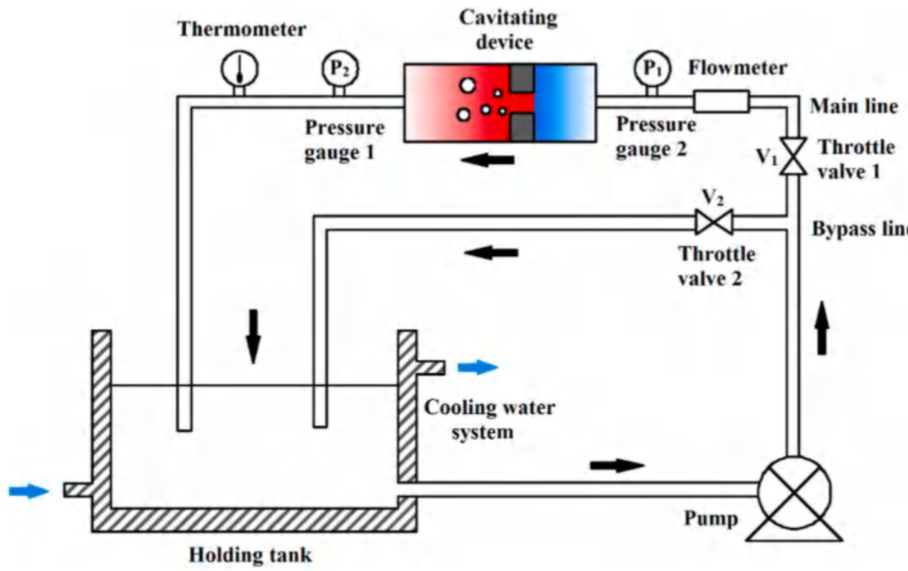

Fig. 1. The experimental setup of hydrodynamic cavitation [48].

dissolution and disintegration degree in sludge with the increasing HC treatment time; (iii) to state the variations of sludge particle size and stability caused by HC; (iv) to analyze the effect of HC on extracellular polymers (EPS) compositions; (iv) to explore the sludge reduction process by HC.

2. Materials and methods

2.1. Sludge sources

The sludge came from the aeration tank in the northern sewage treatment plant (Shenyang, China). The sludge was filtered with a 24 meshes screens to exclude impurities. Additionally, the sludge supernatant also needs be removed after 2 h settlement for the thicken of sludge.

2.2. HC equipment

HC setup was a circulating system consisted of main and bypass lines. HC setup diagram was shown in Fig. 1. The main line included: (1) a water-pump (1.5 kW power, WZB-1500A, Rijin Pump Co., Ltd., China) allowing the liquid to circulate in HC system; (2) an orifice plate with 20 holes of 2 mm in diameter generating HC effect; (3) a pressure gauge measuring the pressure in the main line; (4) a flowmeter quantifying the flow rate; (5) a 20 L holding tank with a cooling water system. Meanwhile, the bypass line could regulate the flow and pressure in the main line. The control group was run without HC generator device (orifice plates), and the HC group was operated with orifice plates. When sludge was passed through the orifice plate on the main line by the self-priming pump, the flow rate could be increased, and the pressure would be dropped below the steam pressure. This would produce a large numbers of cavitation bubbles, and then the cavitation bubble collapsed and caused the HC effect [12,13]. HC group with the orifice plate was performed with an inlet pressure of 3 bar, and control group without the orifice plate were operated for excluding the interference of other factors. The sludge samples in HC group and in control group were collected at 0, 30, 60, 90, 120, 150, 180, 210 and 240 min and were subjected to further analysis.

2.3. Analytical methods

Mixed liquor suspended sludge (MLSS) and mixed liquor volatile suspended solids (MLVSS) in mixed sludge liquor were detected in the light of methods [19]. The chemical oxygen demand (COD) and soluble COD (sCOD) of sludge were gauged in line with the method HACH 8000 [14]. The sCOD measurement need to be filtered with a 0.2 μm

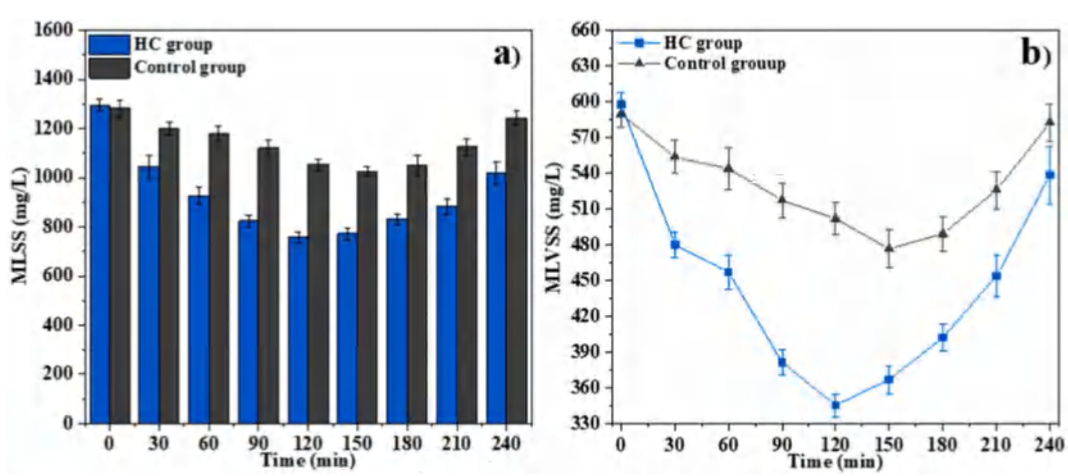

Fig. 2. The variations of (a) MLSS and (b) MLVSS with and without HC.

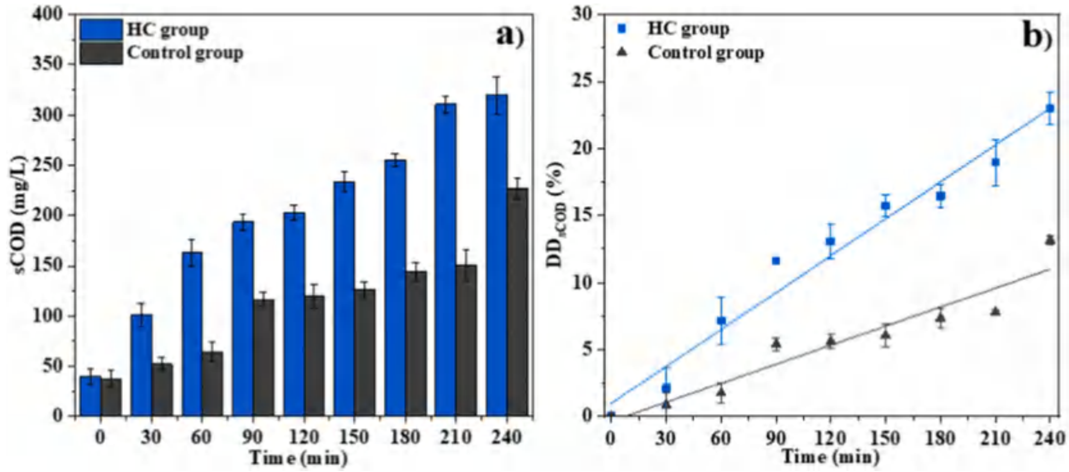

Fig. 3. The effects of HC treatment on (a) sCOD and (b) DD_{sCOD}.

membrane [18]. The sludge particle size distribution was analyzed by the particle size analyzer (Malvern Co., Mastersizer 2000) in the light of ISO 13320-1. The loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS) extraction protocol follows the method in Li and Yang [20]. Determination of protein and carbohydrate in extracted EPS by Lowry-Folin method [21] and the phenol-sulfuric method [22], respectively. 3D excitation–emission matrix (3D-EEM) spectra was measured according to Wang et al. [23]. Sludge morphology was viewed by a scanning electron microscope (SEM, Merlin, Zeiss, Germany) according to Cai et al. [24]. Disintegration degree (DD_{sCOD}) was calculated using the equation below (Eq. (1)) according to Lee et al. [18]:

$$DD_{sCOD} = \frac{sCOD_t - sCOD_0}{COD - sCOD_0} \times 100\% \quad (1)$$

where, COD and $sCOD_0$ (mg/L) were the initial levels of chemical oxygen demand and soluble chemical oxygen demand, respectively; $sCOD_t$ (mg/L) was sCOD level at t minute.

3. Results and discussion

3.1. Effect of hydrodynamic cavitation on sludge reduction

To determine the impact of HC on sludge reduction, the variations of MLSS and MLVSS were analyzed (Fig. 2). In HC group and in control group, MLSS and MLVSS decreased first and then increased as the increase of time. The lowest MLSS in the HC group was 756.86 mg/L at 120 min, while it in the control group was 1026.12 mg/L at 150 min. The decrease of MLSS in the control group was related to the disintegration of sludge by shear stress of water pump mechanical action [25]. Compared with control group, MLSS in HC group was lower, and the time required to reach the lowest MLSS values was shorter. The results suggested both shear stress and HC played an effective role in reducing MLSS from sludge, and HC could promote the MLSS decrease caused by shear stress of water pump mechanical action. Kim et al. [14] found similar results that HC had a better contribution to sludge disintegration than shear stress. MLVSS change trends in HC group and in control group were same as MLSS, and the lowest MLVSS were also found at 120 min and 150 min corresponding to HC group and control group. In HC group, the highest reduction rates of MLVSS and MLSS were 42.13 % and 41.57 % at 120 min, respectively, while in the control group they exhibited 19.13 % and 20.05 % at 120 min, respectively. In HC group and in control group, MLVSS decreased rates were similar to MLSS, suggesting that HC (or shear stress) had analogous disintegration abilities to volatile suspended solid and involatile suspended solid in sludge.

It is interesting that when the reaction time crossed the inflection point (120 min in the HC group and 150 min in the control group), MLSS and MLVSS values of sludge increased gradually with the time increase. At 240 min, MLSS and MLVSS in the HC group were 1018.14 and 538.21 mg/L, respectively, and they in the control group reached to 1243.00 and 582.46 mg/L, respectively. Compared to 120 min in the HC group, MLSS and MLVSS at 240 min increased by 34.52 % and 55.56 %, respectively, and their raised levels in the control group at 240 min were 21.14 % and 22.18 % compared to 150 min, respectively. The increase of MLSS and MLVSS in HC group and in control group suggested a phenomenon of 'fake increase'. HC and shear stress could severely damage to the structure of sludge, resulting in the reduction of sludge particles size [14,26]. The small particles sludge was more likely to absorb moisture [24], leading to increased sludge viscosity [1,5]. The sludge viscosity increase was not propitious to the penetration of sludge through filter membrane [24,27], showing the illusion of re-increasing MLSS and MLVSS of sludge. Compared to control group, 'fake increase' of MLSS and MLVSS in the HC group was more obvious, which was related to the enhancement of sludge disintegration by HC. Although the longer time of HC treatment resulted in more 'false increase' in MLSS and MLVSS, the MLSS and MLVSS values were always lower in HC group compared to control group. The changes indicated that the sludge reduction could be enhanced by HC.

3.2. Effect of hydrodynamic cavitation on sludge organic matters dissolution

To determine the influences of HC on sludge organic matters dissolution, the variations of sCOD and DD_{sCOD} in HC and control group were analyzed. As shown in Fig. 3a, the sCOD concentration in HC group and in control group both increased with the treatment time, and they at 240 min were 319.66 and 227.46 mg/L, respectively. The increases of sCOD in HC group and in control group were mainly attributed to the dissolution of solid phase substances matter due to HC and shear stress [14,28]. In generally, the increase of organic matter and EPS in aqueous phase could contribute to the increase of COD level. The increase in the strength of HC or shear stress could result in the solid phase substances matter disassembly, which caused the concentration increase of organic matter and EPS [12,14]. These could explain why the sCOD levels in HC group and in control group increased as the time.

To further delve the effects of HC on sludge organic matters dissolution, the disintegration degree changes in HC group and in control group were analyze. DD_{sCOD} was the ratio in the concentration changes of sCOD to COD, and it had been widely used to estimate the change of sludge disintegration degree [12]. As shown in Fig. 3b, DD_{sCOD} in HC group and in control group increased by 22.98 % and 13.18 % as the increase of time, respectively. DD_{sCOD} in HC group was higher than in

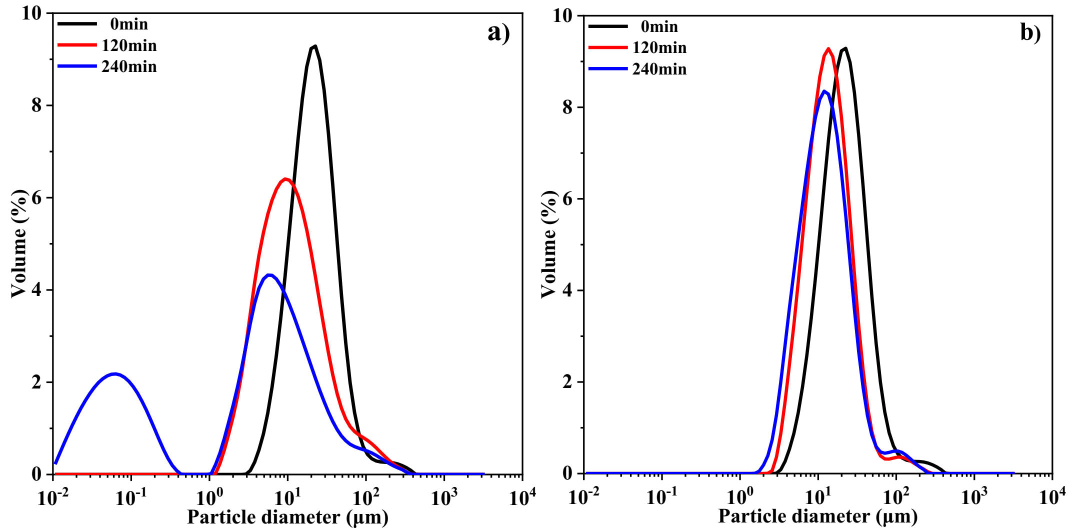

Fig. 4. The variations of sludge particle diameter distribution with and without HC. (a) HC group, (b) Control group.

Table 1
Sludge percentile size changes with or without HC.

Samples	Time	Percentile size (μm)		
		d[a](0.1[b])	d(0.5)	d(0.9)
HC group	0 min	8.97 ± 0.13	21.10 ± 0.34	49.10 ± 0.83
	120 min	3.42 ± 0.00	10.30 ± 0.00	39.55 ± 0.75
	240 min	0.04 ± 0.00	4.45 ± 0.04	26.90 ± 0.00
Control group	0 min	8.10 ± 0.44	19.10 ± 1.00	44.70 ± 2.20
	120 min	5.82 ± 0.18	13.30 ± 0.40	30.70 ± 0.30
	240 min	4.72 ± 0.03	11.85 ± 0.05	30.20 ± 0.10

[a] Sludge size distribution.
[b] The d-values at d(0.1), d(0.5) and d(0.9) represented the particle sizes at the 10th percentile, the 50th percentile and the 90th percentile in particle size distributions, respectively.

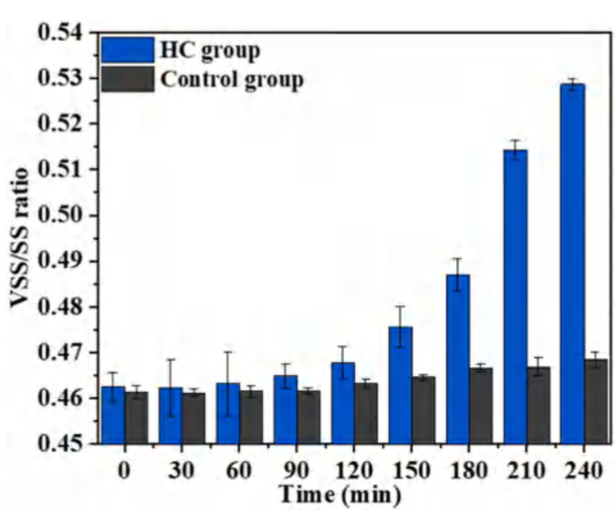

Fig. 5. The variations of VSS/SS ratio in sludge with or without HC.

control group, suggesting that HC promoted sludge disintegration. HC could generate stronger shear stress that damaged bacterial cell walls due to higher velocity, turbulence and partial pressure variations [1,12]. This could explain why the sludge disintegration in HC group was higher than in control group. The sCOD and DD_{sCOD} level were always higher in HC group compared to control group, indicating that HC played a much stronger role in cell disruption and sludge solubilization than shear stress.

3.3. Effect of hydrodynamic cavitation on sludge characteristics

Fig. 4 shows the changes of sludge particle size with and without HC treatment process. Sludge particle size reduced with time in group and in control group. To analyze the sludge particle reduction quantitatively, the particle size percentiles were explored under HC group and control group (Table 1).

The median sludge particle size (d(0.5)) was about 20 μm in untreated sample. In HC group and in control group, d(0.5) decreased as the increase of time, and they were 4.45 and 11.85 μm at 240 min, respectively. The decreased degree of d(0.5) in HC group was higher than in control group. The d(0.1) in HC group was two orders lower than in control group. The results indicated HC and shear stress could result in the reduce of sludge particle diameter by destroying aggregates and flocs of sludge [14,29]. Kim et al. [14] found that shear stress influenced only aggregates and flocs of sludge, whereas HC influenced both sludge flocs decomposition and cell walls destruction. This explained why d(0.1) in HC group was far less than in control group.

Fig. 5 showed the influence of HC on VSS/SS ratio changes. VSS/SS ratio could represent bioorganic matters to total solid ratio [30,31]. The higher the VSS/SS ratio was, the sludge stability was weaker [32]. VSS/SS ratio increased with time, and the VSS/SS ratio in HC group and in control group at 240 min reached to 0.53 and 0.47, respectively. The results showed that HC decreased the sludge stability more significantly than shear stress. At 240 min, d(0.1) value in HC group was significantly decreased (only 0.04 μm), suggesting that more cells might be destroyed by HC [14,24]. The damage of cells caused the leakage of intracellular substances [33], which could result in the increase of biological organic matters [12,33] and the decrease of stability in sludge [16,24,34].

3.4. Effect of hydrodynamic cavitation on extracellular polymers components

Extracellular polymers (EPS) are some high polymers produced by microbes outside the cells [12], which comprises loosely (LB-EPS) and tightly bound EPS (TB-EPS) [23]. EPS has notable influence on the sludge flocs surface properties, the aggregation of microbial cells and the stabilization of floc structure [5,24,35,36]. Proteins and carbohydrates are the indicative components of EPS in sludge [25]. Hence, to systemically explore mechanisms of sludge reduction by HC and shear stress, the proteins and carbohydrates from EPS were characterized.

Fig. 6 shows the effects of HC on the proteins and carbohydrates

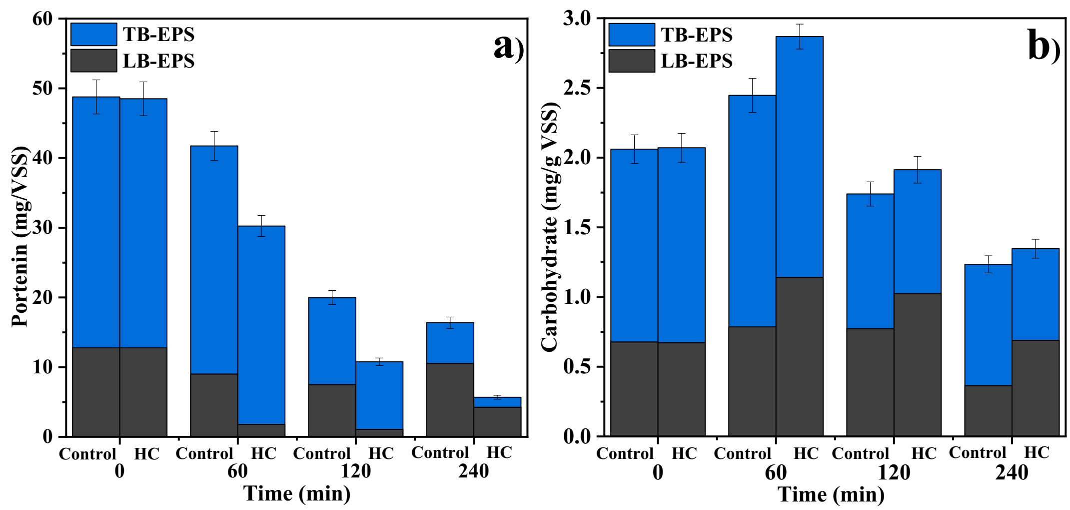

Fig. 6. The variations of proteins (a) and carbohydrates (b) in LB-EPS and TB-EPS with and without HC.

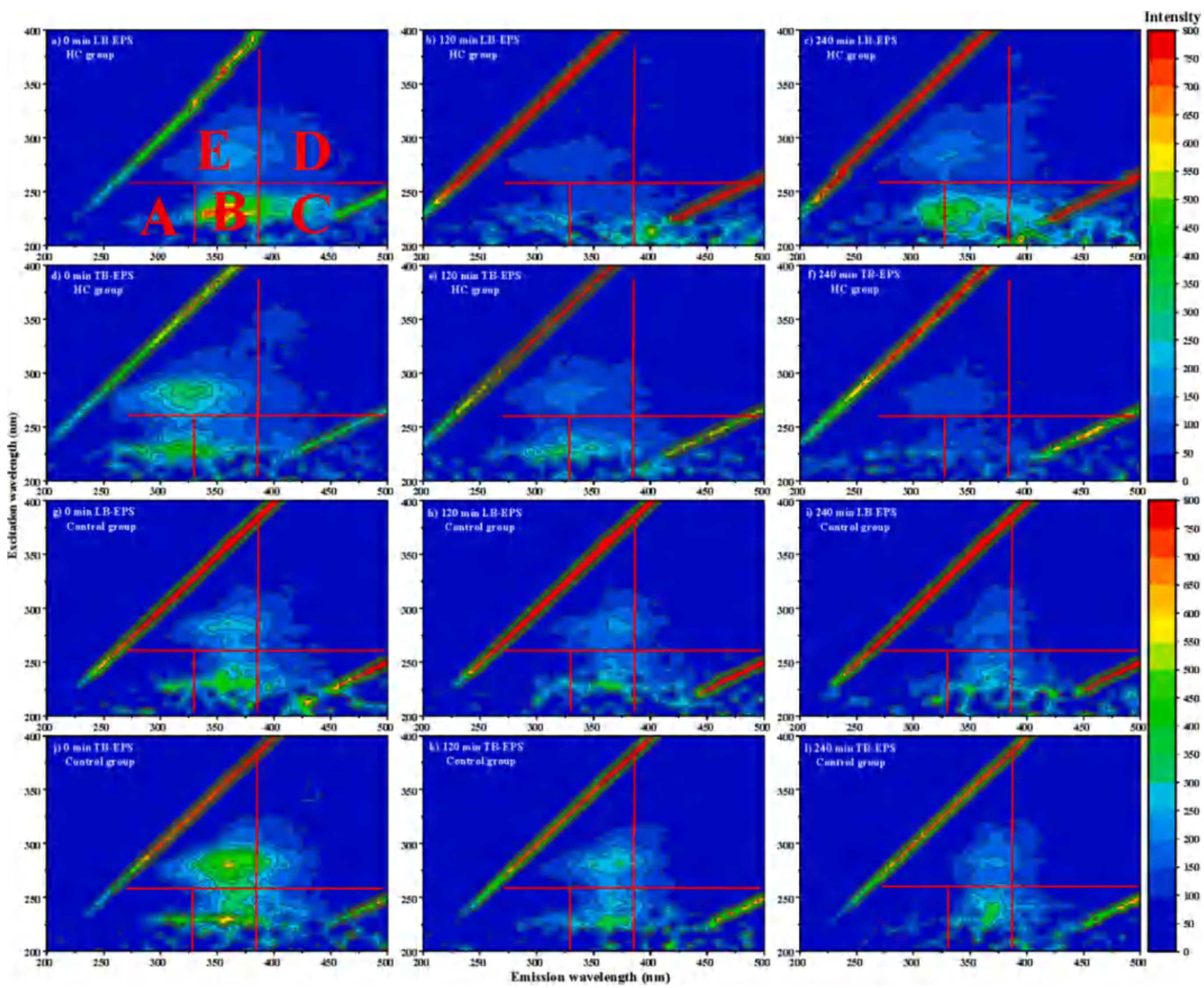

Fig. 7. 3D-EEM fluorescence spectra of LB-EPS and TB-EPS.

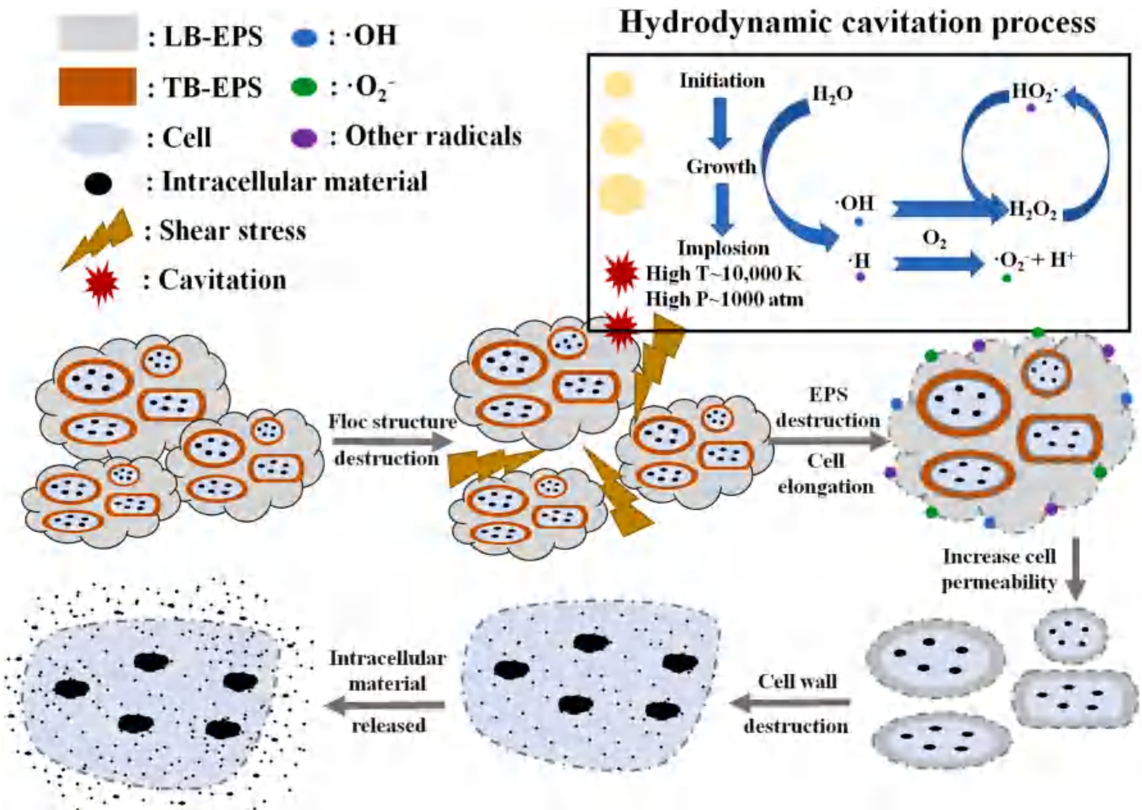

Fig. 8. Possible process diagram of sludge reduction by hydrodynamic cavitation.

concentrations in LB- and TB-EPS. As depicted in Fig. 6a, the protein concentration of TB-EPS in HC group and in control group decreased from 35.74 to 1.42 mg/VSS and 36.00 to 5.85 mg/VSS with the increasing treatment from 0 to 240 min, respectively. Meanwhile, the protein in LB-EPS showed a decreasing tendency first and then gradually increasing one. The PN concentration of LB-EPS in the HC group decreased from 12.76 (0 min) to 1.08 (120 min) and then increased to 4.25 mg/VSS (240 min), and that from the control group reduced from 12.76 (0 min) to 7.49 (120 min) and then raised to 10.53 mg/VSS (240 min), respectively. HC could destroy the protein structure through hydroxyl free radicals and hydrogen free radicals generated by cavitation, which resulted in the decrease of protein concentration in LB- and TB-EPS [24]. This explained why the total protein consistence in LB- and TB-EPS in HC group was lower than in control group. Protein consistence of TB-EPS in HC group always decreased as the increase of time from 0 to 240 min, while that from LB-EPS decreased as the time increase from 0 to 120 min and increased with the time increase from 120 to 240 min. The free protein from fracted cells in solutions could be adsorbed by living cells [37,38]. Considering that TB-EPS and cells were located closer than LB-EPS [39], these proteins would first undergo LB-EPS when adsorbed by cells. This might be one of the reasons that under the significant increase of sludge disintegration degree (from 120 to 240 min), the protein concentration in LB-EPS raised with the time. The carbohydrate consistence in LB- and TB-EPS expressed a trend of increase first and then decrease with the increase of treatment time (Fig. 6b). The increase was related to the disintegration of fucose, rhamnose and arabinose etc. in sludge [40–42]. The carbohydrate concentration in HC group was higher than in control group, implying that HC had a more destructive impact on sludge components than shearing force. Compared to protein, the changed degrees of carbohydrate as the HC treatment time increase were lower, suggesting that HC had a more destructive impact on protein than carbohydrate.

3.5. Effect of hydrodynamic cavitation on 3D-EEM in extracellular polymeric substances

Fig. 7 illustrates the impacts of HC on the changes of 3D-EEM in LB- and TB-EPS. Base on the consistent coverage of excitation and emission wavelength, 3D-EEM was classified into 5 regions: regions A and B were associated with aromatic proteins tyrosine and tryptophan, respectively; region C was related to fulvic acid; region D was described as humic substances; and region E corresponded to tyrosine and tryptophan proteins in soluble microbial products like substances [24,43–45]. In control group, the peaks from LB- and TB-EPS were mainly concentrated in regions B and E at different treatment time, indicating that protein in LB- and TB-EPS was constituted of tyrosine and tryptophan mainly. As the increase of time, the peaks in regions B and E were always found in LB- and TB-EPS, while their strengths were reduced. The changes suggested that in the control group, the treatment time increase did not change protein composition in LB- ans TB-EPS, while decreased the protein levels. In the HC group at 0 min, the peaks from LB-EPS were mainly concentrated in regions B and E, while those in TB-EPS were attributed to regions A and E. As the increase of time in HC group, the peaks in region B from LB-EPS at 120 min and in region A from TB-EPS at 240 min disappeared, suggesting that the HC treatment time increase significantly changed protein composition in LB- and TB-EPS. The changes were related to the fact that the increase of free radical levels along with the production of high temperature and pressure produced by HC could destroyed protein composition and structure [5,46]. In the HC group at 240 min, the peaks in LB-EPS were still attributed to regions A and E compared to that at 0 min. This was similar to the increase of protein levels in LB-EPS from 120 to 240 min in HC group, which might be explained by the free protein from fracted cells in solutions would first be adsorbed by LB-EPS considering that TB-EPS and cells were located closer than LB-EPS.

3.6. Process of HC on sludge reduction

The increase of hole in sludge SEM (Fig. A.1) and the decrease of MLSS and MLVSS values and sludge particle diameter suggested a sludge floc structure destruction by HC, and the reduction of proteins and carbohydrates and the increase of sCOD and DD_{sCOD} values indicated that HC caused EPS destructions and cell elongations. The increased proteins levels in LB-EPS might suggest that an increase of cellular permeability by HC. The sum of proteins and carbohydrates contents from LB- and TB-EPS always reduced with HC time, suggesting that HC could destroy the intracellular materials leaking due to increased cell permeability. Based on the above changes, we inferred that the process of HC on sludge reduction should be that HC firstly caused a sludge floc structure destruction, and then EPS destructions and cell elongations, and finally cell wall destructions (Fig. 8). Previous studies found that HC could cause the increase of free radical levels along with the production of high temperature and high pressure [5,12,47], suggesting that those above factors might be the important driving force about the process of HC on sludge reduction. The mechanism needed to be further studied.

4. Conclusion

HC treatment caused the sludge reduction at 120 min, while there was a fake increase of MLSS and MLVSS levels with HC time during 120–240 min. The increase of hydrodynamic cavitation time could result in the increase of disintegration degree and organic matters dissolution in sludge, and the decrease of sludge particle sizes. The protein level in TB-EPS always decreased with the increasing hydrodynamic cavitation time, while that in LB-EPS decreased firstly and then gradually increased. Hydrodynamic cavitation could destroy tryptophan and tyrosine protein in LB- and TB-EPS.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jwpe.2022.102950.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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