APPLICATION OF A NOVEL HYDRODYNAMIC CAVITATION SYSTEM IN WASTEWATER TREATMENT PLANTS

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In the present work, a novel hydrodynamic cavitation system has been used for the treatment of activated sludge, in order to evaluate the solubilisation of matter, the biodegradability improvement, and the effects on microbial activity. Experiments performed in this study indicate that solubilisation of chemical oxygen demand (COD) increased with specific supplied energy applied. For specific energy input of 1,250 kJ/kg of total solids, the microbial activity of the aerobic and anaerobic bacteria investigated was preserved, while specific energy input of 2,500 kJ/kg of total solids damaged the bacterial cells. Based on the results, in this paper different fields of applications of the novel hydrodynamic cavitation system in wastewater treatment schemes are suggested.

Keywords: Hydrodynamic cavitation, biodegradability, microbial cell disruption, solubilisation,

1. Introduction

Cavitation is generally defined as the phenomenon of generation, growth and subsequent collapse of microbubbles or cavities, resulting in very high local energy densities. When it occurs in a reactor, generates conditions of very high temperature (500-15000 K) and pressures (100 – 5000 atmospheres) locally, but the overall environment remains at the atmospheric conditions [1]. Due to its effects, cavitation has been studied for improvement of wastewater treatment process. Cavitation involves the dissociation of vapour trapped in the cavitating bubbles, resulting in the generation of free radicals which enhance chemical reactions [2]. Further, cavitation results in the generation of local turbulence and liquid micro-circulation in the reactor, increasing the rates of transport processes and, in addition, removing the mass transfer resistances in heterogeneous system

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[3]. Based on the mode of generation, cavitation can be mainly classified in acoustic and hydrodynamic one. Cavitation can be induced in a solution by passage of ultrasound (acoustic cavitation) or by subjecting the liquid to velocity variations by introducing constrictions, such as an orifice plate, venturi or throttling valve, in the flow (hydrodynamic cavitation). Both acoustic and hydrodynamic cavitation have been of academic and industrial interest in wastewater treatment fields [4]. While acoustic cavitation have been widely studied over the past few decades, lower studies are present on hydrodynamic cavitation.

As reviewed by Gogate [4], processes based on hydrodynamic cavitation can be used in wastewater treatment schemes for meeting the high standards of environmental regulations. Hydrodynamic cavitation can be used for a variety of applications ranging from biological applications such as cell disruption to chemical reactions such as oxidation of organic pollutants in aqueous effluents, including biorefractory toxic chemicals. Some studies investigated the use of hydrodynamic cavitation for cell disruption [5], [6] reporting much higher energy efficiencies compared to the acoustic cavitation reactors and to the conventional techniques based on the use of mechanical energy. The energy transfer efficiency of hydrodynamic cavitation reactors is about 60-70% depending on the operating conditions whereas for ultrasonic reactors it is only about 10-40% [7]. Due to its mechanical, chemical, heat effects and its easily implementation, in the recent past, hydrodynamic cavitation has been applied to microbial disinfection of contaminated water. Jyoti and Pandit [8] compared different hydrodynamic cavitation reactors, their efficiency and costs of application with that of ultrasonic reactor and conventional methods of disinfection. The study reported that hydrodynamic cavitation, induced with high-speed homogenizer, is the most cost effective treatment strategy as compared to sonochemical reactors and high-pressure homogenizer and it can be considered a valid alternative to conventional methods for preventing the formation of hazardous by-products. Further, hydrodynamic cavitation can be used as a supplementary technique to conventional biological oxidation to increase the biodegradability of wastewaters [9], [10]. Nevertheless, compared to the acoustic cavitation, it appears that the processes based on hydrodynamic cavitation have to be improved. Engineers have generally been looking with caution at cavitation in hydraulic devices due to the problems of mechanical erosion. A good design and fabrication of a hydrodynamic set-up differing in flow field, turbulence characteristics and geometry are needed to enhance the use of this process as a good supplement process for cell disruption, microbial disinfection, to enhance the biodegradability and consequently to improve the biogas production in the anaerobic digestion or the denitrification process in the activated sludge process.

Officine Parisi have recently proposed a novel full scale hydrodynamic cavitation reactor based on a particular geometry of the constriction which creates multi-dimensional vortices of liquid that never hint the walls of the cavitation reactor, avoiding the problem of the erosion, allowing to harness the impressive effects of hydrodynamic cavitation for chemical-physical transformations. Thus, the aim of the present study is to evaluate the application of a novel hydrodynamic cavitation system in wastewater treatment plants (WWTP) in order to verify its effects on the solubilisation of organic compounds, the biodegradability and the microbial activity.

2. Materials and Methods

2.1 Characteristics of the liquid

Experiments on hydrodynamic cavitation were performed on the activated sludge collected from the municipal WWTP of Trento, Italy. The activated sludge used in this study had an initial suspended solids concentration of 6g TSS / l. It was previously stored in a tank and subjected to sedimentation by gravity for 24 h. The supernatant was removed through the use of taps, earlier installed on the tank at different heights. The sludge had a final suspended solids concentration equal to 10-11 g TSS / L of. The concentrated sludge used in this study had 199 mg/l of filtered COD, 19 mg/l of total ammonium as nitrogen (TAN), 11 g/l of TSS, 6.6 pH, temperature equal to 16°C and a redox value of -150 mV.

2.2. Experimental set-up

The experimental setup is illustrated in Figure 1. The system is basically composed by a storage tank for liquid (1 m^3) and a full scale hydrodynamic cavitation disposal. The concentrated activated sludge is pumped into the cavitation device by using two pumps in sequence of 2 x 1.5 kW with a flow of 8 m^3/h and a total pressure of 6 bar. Fig. 2 shows schematic details of the actual cavitation device, a multi-dimensional vortices generator. The tool has an area (i) to generate the multi vortices, which is limited by an injection piece and an orifice plate. The created whirl field will be accelerated in the cone section (ii - iii). The diffusor section (iii) improves the cavitation effect, before the flow will be fascicled (vi) to be moved into the outflowing pipe. The full establishment of the field of vortices causes a cavitation effect to the whole flow surface. This leads to a uniform high degree of fragmentation and degradation. This effect works on water clusters, agglomerations of fibers and molecules. Further, the field of vortices allows at the same time to mix chemicals into the flow. The field of helical vortex produces more than 1000 pulses per second causing a more intense penetration of water in the chemical and therefore a better mixing of the solid with the liquid. Finally, the rest of the vortex power could support the injection of the fluid in a main pipe stream.

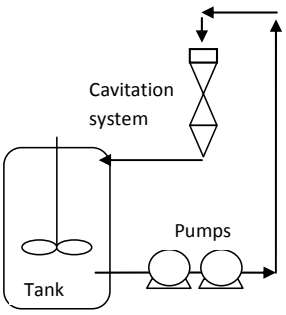

Fig. 1. Schematic of the hydrodynamic cavitation setup

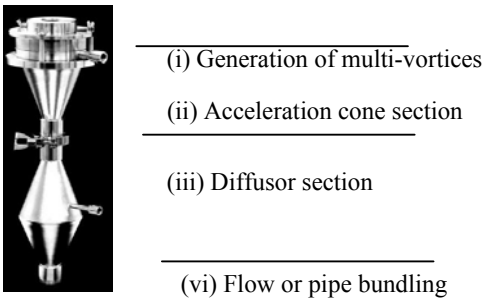

Fig. 2 Schematic of the cavitation device

2.3. Experimental and analytical methodology

Hydrodynamic cavitation based treatment of wastewater was carried out by using 800 L of concentrated activated sludge, without temperature regulation. After a first mixing phase (without cavitation), an homogeneous sample was taken to evaluate the parameters at t=0, therefore, TSS, COD and TAN. The sludge was continuously subjected to hydrodynamic cavitation for a circulation time through the device of 2 h. Samples were taken at regular intervals: 40 minutes, 1 h, 1.5 h, 2 h. Specific supplied energy (E_s) ranged from 0 to 2,500 kJ/kg TSS. Specific supplied energy has been chosen in order to compare results. E_s is defined using hydrodynamic power (P), hydrodynamic time (t), sample volume (v) and initial total solid concentration (TSS_0):

$$E_s = \frac{P \cdot t}{v \cdot TSS_0} \tag{1}$$

2.4. Solubilisation of organic compounds

Calculation were performed to study the efficacy of hydrodynamic cavitation on solubilisation of organic compounds in activated sludge. According to Bougrier et al. [11], COD solubilisation (S_{COD}) and degree of disintegration (DD_{COD}) were determined. COD was measured in the raw sludge, in the supernatant liquor, "soluble COD" (COD_s), and in the particulate fraction, "particulate COD" (COD_p). COD solubilisation (S_{COD}) represents the transfer of COD from the particulate fraction of the sludge to the soluble fraction of the sludge. S_{COD} was calculated using the difference between COD_s and initial soluble COD_{s0}, compared to the initial COD_{p0}:

$$S_{COD} = \frac{COD_s - COD_{s0}}{COD_{p0}} \cdot 100\%, \tag{2}$$

The degree of disintegration (DD_{COD}) was defined as the comparison between cavitation process and the maximum soluble chemical demand (COD_{NaOH}) obtained by alkaline hydrolysis [12]:

$$DD_{COD} = \frac{COD_s - COD_{s0}}{COD_{NAOH} - COD_{s0}} \cdot 100\%, \quad (3)$$

COD NaOH is the COD in the supernatant of the reference sample. For alkaline hydrolysis, sludge was mixed with NaOH (1 mol/l), for 24 h, at room temperature.

2.5. Specific oxygen uptake rate (SOUR)

Respirometric analyses were carried out to compare both the microbial activity of aerobic heterotrophic bacteria and the increase of the biodegradability of the activated sludge due to the cavitation effects. The respirograms of the activated sludge at time t = 0 and after 1 h and 2 h of cavitation (time t = 1h, t = 2h) were determined according to Andreottola et al. [13]. Due to the high concentration of solids present in the samples, an initial dilution was performed, using purified water previously filtered through a 0.45 μm pore size membrane filter (the use of this water does not constitute an additional oxygen demand). The respirometric activity of the microbial population was evaluated using a 1.2 l respirometer, containing the dilute sample, which was homogenised with the aid of a magnetic agitator. The total solids concentration of the diluted samples was in the range between 2.3-3.0 g TSS / l. The respirometer was equipped with an air diffuser and an air compressor. DO, pH and temperature were measured in the liquid through the DO probe. The DO probe was connected through a RS-232 port to a computer, which was used for storing and monitoring all data. Temperature was kept constant at 20°C and the pH between 7.5 and 8. For all the experiments, thiourea (20 mg L^{-1}) was added to inhibit the nitrification process. The DO depletion in the vessel, due to the substrate (organic carbon) utilization, was monitored over the time. First, the Oxygen Uptake Rate (OUR), expressed as mgO_2 / l h, was determined by the slope of the plot of DO concentration versus time after stopping for few minutes the air flow inlet [13]. Then, the specific OUR (SOUR),), expressed as mgO_2 / gTSS h, was obtained dividing the OUR by the TSS concentration in the assays.

2.6. Sulfate reduction activity assays

In order to evaluate the effect of hydrodynamic cavitation on the activity of a group of anaerobic microorganisms potentially involved in the process of biological minimization of the sludge, i.e., the sulfate reducing bacteria (SRB), sulfate reduction activity assays were conducted at time t = 0 and after 1 h of cavitation (time t = 1h). Sludge (3.5 l) was transferred to flasks (5 l). The flasks were sealed with butyl rubber stoppers and soluble substrates added from sterile 100 g / l stock solutions (Na_2SO_4 and CH_3COONa). Directly hereafter, the flasks were made anoxic by flushing with N_2 gas. All incubations were performed at room temperature (T=20°C), under continuous mixing (150 rpm) and at a constant initial pH of 7.0. Activities were determined by measurement, in batch tests, of

the rates of depletion of sulphate (SO_4^{--}) and COD. To this end, measurements were performed over a time span of 3 h with a sampling interval of 30 min. Batch tests were performed using a constant initial concentration of SO_4^{--} (110-120mg/lSO_4^{--}). Each test was conducted in duplicate. Two batch tests were carried out using the untreated activated sludge at t=0: a test without an external carbon source and a test adding an external carbon source in the ratio COD/ SO_4^{--} of 1.5, which is the optimum for SRB. Finally, one batch test was carried out using the cavitated activated sludge at t=1h, without any external carbon source.

2.7. Analytical methods

Total suspended solid (TSS) concentration was determined according to the Standard Methods [14]. The samples were filtered through 0.45 μm filters. The filtrate was analyzed colorimetrically for TAN [15] and chemical oxygen demand ($COD_{filtrate}$) [14]. Sulphates were analyzed by ion chromatograph. Redox potential, pH and temperature were measured using portable instruments.

3. Results and discussion

3.1. Solubilisation of organic compounds

For each experiment, while the energy input increased, total COD was constant. During the experiments, the soluble/particulate COD repartition varied: COD_s increased, whereas COD_p decreased. The COD_s increased constantly with the increase of the specific supplied energy, from 200 mg COD / l at t=0 to 407 mg COD / l at t=2h. Solubilisation and degree of disintegration are reported in Fig. 2. For E_s of 2,500 kJ/kg TSS, solubilisation and degree of disintegration reached a value of 1.7% and 2.5%, respectively. These values are low but similar to those obtained in other studies that had investigated ultrasonic treatment on activated sludge at low specific supplied energy [11], [16]. For E_s over 2,500 kJ/kg TSS, solubilisation and degree of disintegration remain to be investigated.

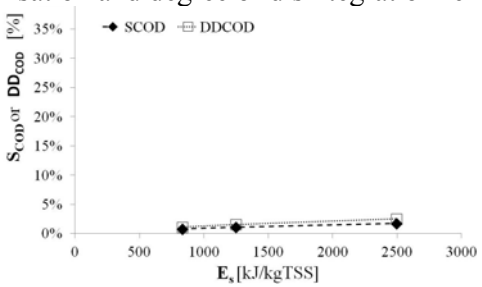

Fig. 3. Solubilisation and degree of disintegration of COD vs specific supplied energy

Further, the TAN concentration in the liquid phase was monitored. Hydrodynamic cavitation breaks cell. Intracellular compounds are released into the liquid phase and are made soluble. Nitrogen is mainly in proteins or amino acids (organic nitrogen). Thus, proteins could be broken by hydrodynamic cavitation (solubilisation) and could be degraded and transformed in ammonia. In

this study, we observed that TAN concentration in the liquid fraction increased with the specific supplied energy, confirming that hydrodynamic cavitation led to a transformation of organic nitrogen into ammonium (degradation). However the nitrogen degradation was little, in fact while the $CODs/COD_0$ ratio increased strongly, the TAN/TAN_0 ratio increased slowly. In order to obtain a clear result on nitrogen solubilisation and a nitrogen distribution as function of specific supplied energy, the organic nitrogen content and the total kjeldahl nitrogen (TKN) remain to be monitored together with TAN concentration.

The increase of soluble forms of carbon and nitrogen may be attributed for low specific supplied energy to floc disintegration and especially to extracellular polymeric substances (EPS) destructuration rather than cell lysis [16]. On the contrary, for high specific supplied energy both the effects should be taken into account. Table 1 summarizes the results obtained.

Table 1

Solubilisation and degree of disintegration

Test	E_s [kJ/kgTSS]	TSS [g/L]	CODs [mg/l]	TAN [mg/l]	S_{COD} [%]	DD_{COD} [%]
t=0	0	11	199	19	0	0
t=0.66 h	831.8	n.d.	291	20	0.75	1.10
t=1 h	1247.7	11	326	25	1.04	1.52
t= 2h	2495.4	10	407	28	1.71	2.50

3.2. Microbial activity

The SOUR endogenous measured by respirometric assays on the untreated activated sludge sample was 3.11 mg O_2 / g SST h. This parameter is linked to the aerobic activity of heterotrophic bacteria. Applying the hydrodynamic cavitation, for specific energy lower than 1,250 kJ/kg TSS, the SOUR endogenous was equal to that of the sample untreated, while the SOUR decreased by half when the specific energy was 2,500 kJ/kg TSS (Figure 4). We demonstrated that a E_s lower than 1,250 kJ/kg TSS is used to break the flocs and (EPS) destructuration rather than to lyses cells. Higher energy can lead to lyses cells, decreasing the microbial activity of aerobic heterotrophic bacteria.

A similar observation can be made with respect to the activity of the anaerobic SRB. The SRB activity measured for an E_s of 1,250 kJ/kgTSS was equal to the SRB activity of the untreated sample (0.9 mg SO_4^{--}/ g TSS h), meaning that, for this energy value, hydrodynamic cavitation does not destroy the bacterial cells.

3.3. Sludge biodegradability

As it was shown before, hydrodynamic cavitation induced solubilisation of organic matter and consequently, it is supposed to improve the sludge biodegradability. In this study, the increase of the biodegradability is confirmed by the microbial activity tests. For an E_s of 1,250 kJ/kgTSS (t=1h), that does not compromise the microbial activity and the endogenous respiration, the results of

the respirometric tests and the anaerobic sulphate reduction activity assays can be used to evaluate the biodegradability improvement due to the hydrodynamic cavitation. In respirometric tests, the total biodegradable COD was measured from the respirograms, shown in fig. 4 (a,b).

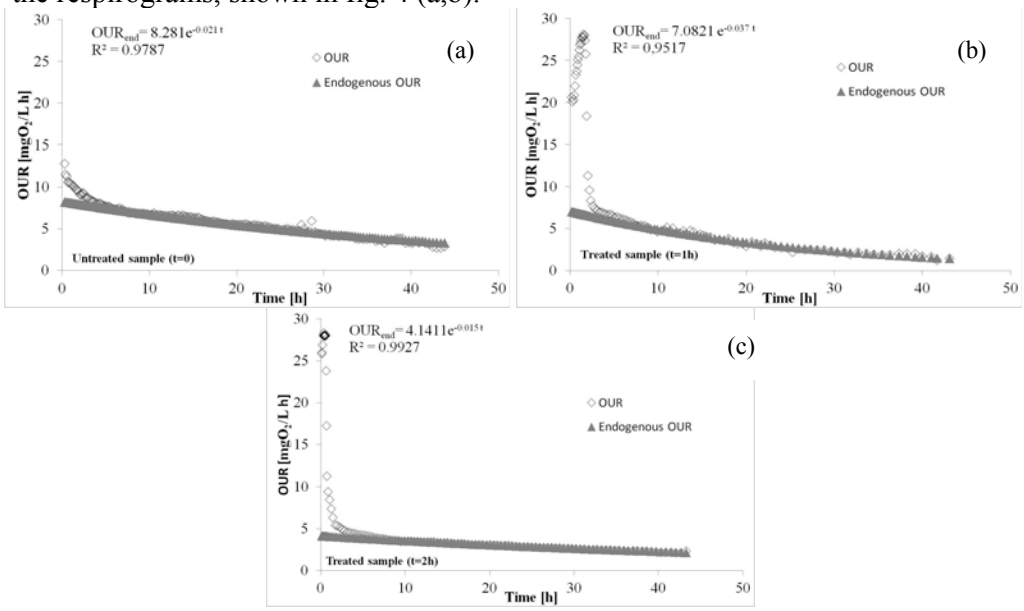

Fig. 4. Respirograms of (a) untreated activated sludge; (b) treated activated sludge after 1h of cavitation; (c) treated activated sludge after 2h of cavitation.

The OUR values from the beginning to the end of the tests comprised exogenous and endogenous respiration. The exogenous oxygen consumption (ΔO), due to the consumption of organic biodegradable compounds, was evaluated subtracting the contribution of the endogenous respiration from the whole oxygen consumption (the area under the OUR curve). The exogenous oxygen consumption was then converted to equivalent COD using the expression based on a COD mass balance [17]. For the specific supplied energies of 1,250 kJ/kgTSS (t=1h), it can be seen an increase of the area under the OUR curve with respect to the area measured for the untreated sample. This increase of the area corresponds to an increase of the biodegradable COD from 58 to 326 mg COD / l (table 2).

The increase of the biodegradability was also confirmed by the anaerobic sulphate reduction activity tests. The results obtained at t=0 show that the internal COD of the untreated activated sludge was not biodegradable, and the sulphate reduction only took place when an external carbon source has been added. On the contrary, after 1 hour of cavitation and at an E_S of 1,250 kJ/kg TSS, we observed that, without any external carbon source, the sulphate uptake rate was comparable to that measured using the untreated sample, for with an external carbon source

had been added. This result demonstrates the increase of biodegradability of the activated sludge treated with hydrodynamic cavitation (table 2).

Table 2

Time [h]	E_s [kJ/kgTSS]	TSS [g/L]	Respirometry		SRB activity assay		
			OUR [mgO_2/g TSS h]	CODbiod [mg/l]	Initial SO_4^- [mg/l]	Initial CODs [mg/l]	r_{SO4--} [mg/gTSS h]
0	0	11	3.11	58	122 (external SO_4)	522 (external C)	-0.9
0	0	11			110 (external SO_4)	456 (internal C)	-0.01
1	1247.7	10	3.13	326	121 (external SO_4)	447 (internal C)	-0.9

4. Conclusions and future developments

In the present work a full scale hydrodynamic cavitation device has been applied to treat the activated sludge of a municipal WWTP. The novel hydrodynamic cavitation system was shown to have an effect on sludge solubilisation, on biodegradability improvement and on microbial activity, depending on the specific supplied energy, that can be considered the main parameters for defining the field of application. COD and ammonium concentration increased with the supplied energy. In the same time, the biodegradability of the sludge increased too. In fact, the hydrodynamic cavitation process led to floc size reduction, EPS destructuration and cells lysis, releasing organic substances into the liquid phase. Organic substances are more available, so biodegradability is improved. In term of microbial activity, the threshold valued of the specific supplied energy, in the conditions of this study, is about 1,250 kJ/kTSS. Values below the threshold cause the COD solubilisation, due to flocs size reduction and EPS destructuration, without damage of the microbial biomass. On the contrary, values above 1,250 kJ/kgTSS involve the COD solubilisation and cell lysis, compromising the activity of microorganisms.

These results are of use to define the application of hydrodynamic cavitation in a WWTP scheme. For low specific energy, hydrodynamic cavitation is suggested to be installed directly in biological reactors, such as denitrification and anaerobic digestion tanks. In both cases, it enhances the biodegradability of the sludge and the mixing phase, without damage bacteria. On the other hand, using a high specific energy, it is possible to apply the hydrodynamic cavitation in a reactor side-stream in order to maximize the production of biodegradable COD, enhancing the microbial cell lysis. For high specific energy, the system could also be used for microbial disinfection. An alternative use of cavitation could be as a pre-treatment before anaerobic digestion of food waste [18] as this biomass could take a clear advantage from the variation in granulometric characteristics from cavitation application, compared to other biodegradable streams [19].

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