EXECUTIVE REVIEW OF HYDROSTATIC PRESSURE EFFECTS ON SLUDGE PRETREATMENT BY SONICATION

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ABSTRACT

Related to ultrasonic (*US*) pretreatment of sludge, changing the hydrostatic pressure will change the resonance condition of cavitation bubbles and then may drive the system toward resonance conditions, consequently increase the rate and yield of reactions. Nevertheless, nearly all the *US* experiments had been carried out at atmospheric pressure. Only a few studies had been focusing on how increasing static pressure affects cavitation. The effect of hydrostatic pressure on sludge disintegration was studied for the first time in the last few years. This work aimed at reviewing the effect of pressure on sludge ultrasonic pretreatment efficiency in different conditions. The major result was that the optimum pressure depends on power input -P_{US}, intensity -I_{US} (or probe size), and temperature -*T*, but not on specific energy input -*ES*, frequency -F_S, nor sludge type. In general, sludge disintegration efficacy was significantly improved by sonication at the optimum pressure, especially at low *ES*, leading to a potential of energy input savings in sludge sonication pretreatment, but also in most of ultrasound assisted processes.

Keywords: hydrostatic pressure, sludge disintegration, sludge pretreatment, sonication, ultrasonic pretreatment, waste activated sludge

1. INTRODUCTION

Despite ultrasonic (*US*) sludge treatment has reached commercial developments and given rise to many works, and hydrostatic pressure is known as an important parameter, but had hardly been investigated. Thereby, it is necessary be elucidated or confirmed in order to optimize sludge disintegration: Is there an optimum hydrostatic pressure for sludge US pretreatment? If any, how do the other parameters (sludge type, sludge concentration, temperature -*T*, specific energy input -*ES*, power input -P_{US}, intensity -I_{US}, frequency -F_S) affect this optimum and what is the expected gain in terms of energy saving?

Changing the hydrostatic pressure will change the resonance condition of cavitation bubbles and then may drive the system toward resonance conditions [1], consequently increase the rate and yield of reactions [2 - 4]. More probably, both the cavitation threshold and intensity should increase following an increase in pressure [5], suggesting a possible optimum pressure. Brett and Jellinek [6] stated that bubbles could be visible for gas-applied pressure as high as 16 atm. Nevertheless, nearly all the *US* experiments have been carried out at atmospheric pressure. Only a few studies have been focusing on how increasing static pressure affects cavitation.

The effect of pressure on sludge ultrasonic pretreatment have been investigated in the last few years. This paper presents an executive review of sludge pretreatment by sonication under pressure, including the relationships between pressure and sludge types, *ES*, P_{US}, I_{US}, *T*, and F_S for optimization of sludge *US* pretreatment efficiency

2. EFFECT OF PRESSURE ON SONICATION EFFICACY

Most works on pressure effects concern sonoluminescence and no consensus emerges about an optimum value as reported by Chendke and Fogler [7 - 8]. The early works of Finch [9] indicated the greatest sonoluminescence intensity to be observed in water at about 1.5 atm, but Chendke and Fogler [8] recommended 6 atm in nitrogen-saturated water. In aqueous carbon tetrachloride solutions, the sonoluminescence intensity did not show any monotonous behavior: two peaks at 6 and 12 atm, and almost inhibited above 18 atm [7]. Increasing superimposed hydrostatic pressures (up to 47.5 bar) resulted in a decrease in volume fraction of cavities [10], then the cavitation damage level in superplastic [11 - 12]. On the other hand, a strong effect of hydrostatic pressure on cavitation was found, *e.g.* optimum pressure of 4.5 atm for a maximum aluminum foil erosion rate [13] or 4 bar for 304L stainless steel corrosion rate [14]. Hydrostatic pressure retards both cavity nucleation (reduction of the total number of cavities) and cavity growth (decrease in the sizes of cavities). As a result, larger *US* intensity is required to induce bubble oscillations and implosions.

More recent pressure effects again focused attention. Gaitan *et al.* [15] found the collapse strength to be intensified at elevated pressures in part due to an increased differential pressure between the external liquid and the interior of the bubble. Extended the work of Gaitan *et al.* [15], Bader *et al* [16] found the increased acoustic energy stored in the resonant system (*i.e.* increased peak negative pressure) to be the main reason rather than the increased differential pressure. The overpressure acts to suppress cavitation and increase the amount of stored energy which leads to an increase in the collapse strength and therefore shock wave amplitudes. Besides, the cavitation threshold increases linearly with the static pressure, thus the acoustic pressure amplitude required to reach the cavitation threshold also increases [17]. Yasui *et al.* [18] showed the optimal static pressure which maximizes the acoustic energy increases as the acoustic amplitude increases or viscosity of liquid decreases, which qualitatively agrees with Sauter *et al.* [19].

Closer to the present subject, Neppiras and Hughes [20] investigated the influence of pressure (up to 5.8 atm) on the disintegration of yeast cells and found an optimum value of 4 atm. As mentioned, the effect of pressure on sludge *US* pretreatment had hardly been investigated until recent years. The following contents presents its effects in different conditions. The best conditions (combinations) to obtain are expected to enhance sludge disintegration and then to save energy input as sludge pressurization needs only little energy.

3. EFFECT OF PRESSURE ON SONICATION PRETREATMENT OF SLUDGE

3.1. Effect of hydrostatic pressure on DD_{COD} for different *ES* values and sludge types

Le *et al.* [21] used mixed sludge to evaluate the effect of pressure on disintegration *vs.* sonication time. For these tests, 52 experiments were respectively conducted at various *ES* for different pressure values: 2 bar intervals were used first and then 1 bar intervals at *ES* of 35000 kJ/kg$_{TS}$. The results are presented in Fig. 1, where DD_{COD} is plotted as a function of pressure for different *ES* values.

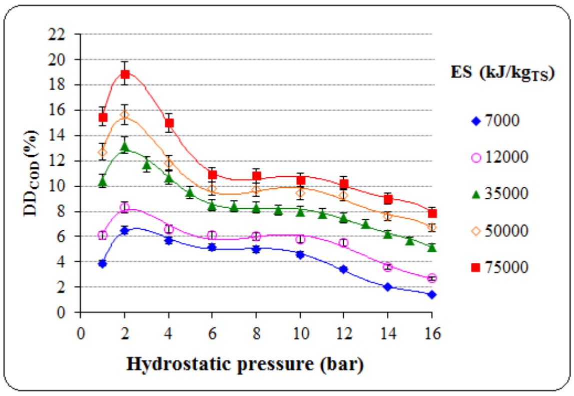


Figure 1. Effect of hydrostatic pressure on mixed sludge disintegration (DD_{COD}) for different final *ES* values: P_{US} = 150 W, 35mm diameter probe (*BP*), F_S = 20 kHz, *TS* = 28 g/L, and *T* = 28±2°C [21].

All corresponding curves show the same trends of DD_{COD}: an initial increase up to 2 bar and a decrease thereafter, noticeably up to 6 bar, before a plateau from 6 to 10 bar approximately and a further decrease. The main result is that for this *US* equipment and application, almost the same value of optimum pressure was found regardless of *ES*. It is also noteworthy that pressure effect appears relatively high at low *ES*, with a maximum improvement of 67 % at 7000 kJ/kg$_{TS}$ and much lower at 75000 kJ/kg$_{TS}$ (23 % gain). In addition, the positive effect of pressure up to 2 bar might lead to energy savings in sludge *US* pretreatment. For instance, at the optimum pressure, DD_{COD} obtained with *ES* of 7000, 35000, and 50000 kJ/kg$_{TS}$ were higher than those at atmospheric pressure with *ES* of 12000, 50000, and 75000 kJ/kg$_{TS}$, respectively. It is also interesting to note that the decrease of DD_{COD} beyond the optimal pressure was faster at higher *ES*..

Additional *US* experiments on secondary sludge were performed to check for the possible dependence of the pressure effect on sludge type. The results, shown in Fig. 2, indicated that the optimal pressure was again about 2 bar regardless of sludge type also.

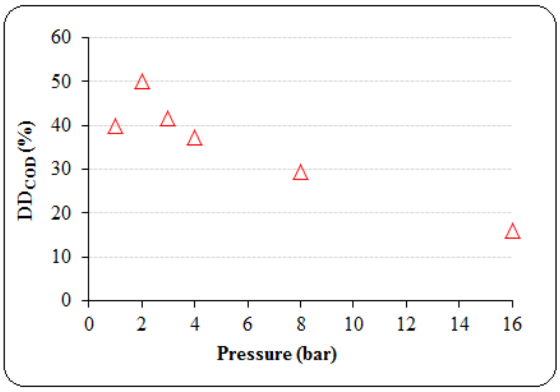
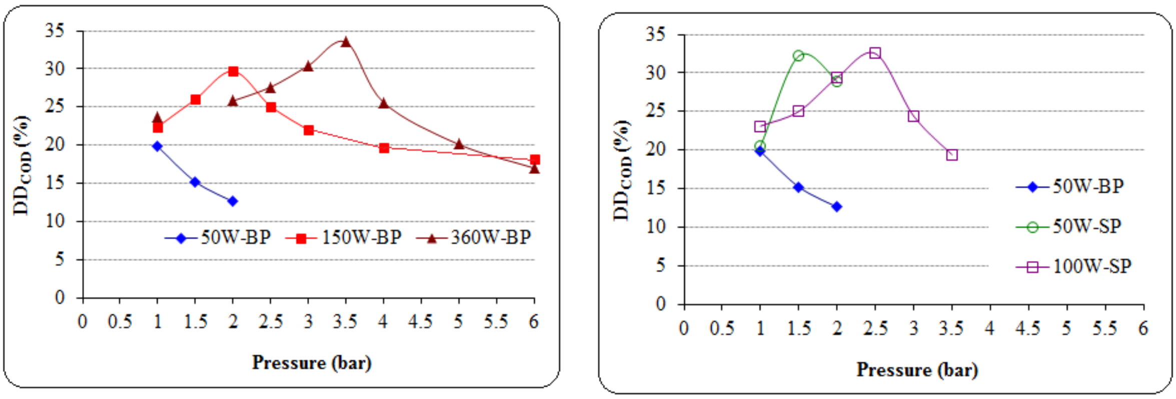


Figure 2. Effect of hydrostatic pressure on secondary sludge disintegration (DD_{COD}): P_{US} = 150 W, BP, ES = 75000 kJ/kg_{TS}, F_S = 20 kHz, TS = 28 g/L, and T = 28 ± 2 °C.

3.2. Effect of *US* power and intensity on the optimal pressure and subsequent DD_{COD}

This section presents dependences of optimal pressures on P_{US} and I_{US} when also varied by changing probe size at same P_{US}, investigated by Delmas *et al.* [22]. Sonication (20 kHz) was applied on secondary sludge at the same *ES* of 50000 kJ/kg_{TS} varying hydrostatic pressure between 1 and 6 bar (with 0.5 bar intervals). Results are presented in Fig. 3.



(a) (b)

Figure 3. Effect of hydrostatic pressure on DD_{COD} of secondary sludge for different P_{US} and probe sizes (F_S = 20 kHz, ES = 50000 kJ/kg_{TS}, T = 28°C, and TS = 28 g/L): (a) BP, (b) 13 mm diameter probe (SP) and BP at same P_{US} [22].

Figure 3 indicates that the optimum pressure is a function of both P_{US} and probe size. First with the same probe (*BP)*, the optimum shifts toward higher pressure when increasing P_{US} (and thus I_{US} proportionally): 1 bar (or even lower) at 50 W, 2 bar at 150 W, and 3.5 bar at 360 W (Fig. 3a). At the much higher intensity delivered by *SP*, the optimum pressure was found at 1.5 bar at 50 W and 2.5 bar at 100 W (Fig. 3b). The decrease in DD_{COD} observed when raising pressure above atmosphere with *BP* at 50 W clearly shows the expected positive effect of pressure only occurs at sufficient I_{US} (or acoustic pressure), unless cavitation intensity decreases. In other words, at same P_{US} (50 W), different effects of pressure resulting from different emitter surfaces indicate the dependence of optimum pressure on I_{US}. Sonication under convenient excess pressure significantly improves sludge disintegration compared to atmospheric sonication, especially at high I_{US} and at low *ES* as previously found in Fig 1*:* up to 95% and 56% of DD_{COD} improvements for *SP* and *BP*, respectively (Fig. 4). Interestingly, at optimum pressures, better sludge disintegration was found at 50 W (*SP*) than at 150 W (*BP*).

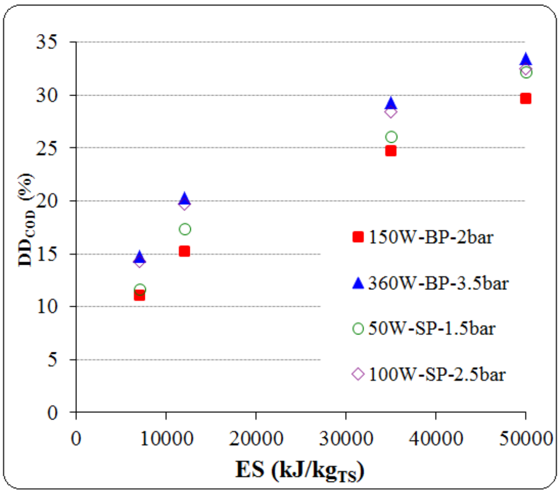


Figure 4. Disintegration degree of secondary sludge as a function of ES at the optimal pressures of each configuration (P_{US}, probe size): F_S = 20 kHz, TS = 28 g/L, and T = 28 ± 2 °C.

Figure 5 depicts the effect of I_{US} under different pressures at same P_{US} (50 W) on secondary sludge disintegration. First, the role of I_{US} (at same P_{US} of 50 W with different probe sizes, corresponding to I_{US} of 5.2 and 37.7 W/cm^2) is insignificant at atmospheric pressure. However, its effect around the optimal pressure becomes extremely high, *e.g.* at 50000 kJ/kg_{TS}, DD_{COD} obtained with *SP* is 2.1 and 2.3-fold higher than with *BP* at 1.5 and 2 bar, respectively. Such effect, much higher than that of P_{US} at atmospheric pressure, highlights the complex interplay of the various parameters on cavitation efficiency.

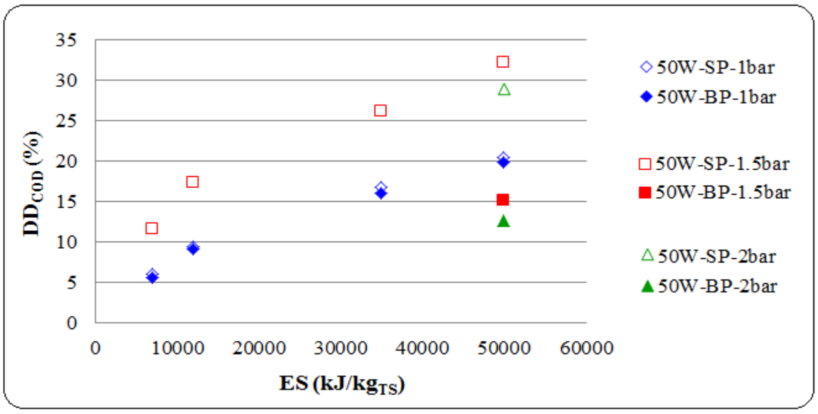


Figure 5. Effect of ES, US intensity (at same P_{US}) and pressure on secondary sludge disintegration: F_S = 20 kHz, TS = 28 g/L, and T = 28 ± 2 °C.

According to Lorimer and Mason [5], increasing hydrostatic pressure leads to an increase in both the cavitation threshold and the intensity of cavity collapse, which can be explained as follows: when an acoustic field is applied to a liquid, the sonic vibrations create an acoustic pressure *(P_a)* which must be considered to be additional to the ambient hydrostatic pressure *(P_h)* already present in the medium. Theoretical calculations from Noltingk and Neppiras [23], Flynn [24], and Neppiras [25], assuming an adiabatic collapse of the bubbles, allow estimating the temperature *(T_{max})* and pressures *(P_{max})* within the bubble at the moment of total collapse according to:

$$T_{\max} = T_o \left\{ \frac{P_m\ (\gamma - 1)}{P} \right\} \qquad P_{\max} = P \left\{ \frac{P_m (\gamma - 1)}{P} \right\}^{\left(\frac{\gamma}{\gamma - 1}\right)}$$

where T_o is temperature of the bulk solution, γ is the ratio of specific heats of the gas (or gas vapour) mixture, P is the pressure in the bubble at its maximum size and usually assumed to be the vapour pressure of the liquid, P_m is the total solution pressure at the moment of transient collapse ($P_m \sim P_h + P_a$).

Thereby, increasing P_h leads to an increase in P_m, thus P_{max} and T_{max}, *i.e.* cavitation intensity. On the other hand, as abovementioned, increasing P_h also results in an increase in cavitation threshold, thus the amplitude of acoustic pressure (P_A directly depending on I_{US}) should be in excess as compared to hydrostatic pressure for cavitation bubbles to be generated: indeed it can be qualitatively assumed that if P_h - $P_A > 0$, there is no resultant negative pressure and cavitation cannot occur.

All these combined effects explain why different I_{US} values resulting either from a change of P_{US} or probe size lead to different optimal pressures (Fig. 3) and why I_{US} effect at given P_{US} becomes important when moderately raising the pressure, resulting in an inhibition of cavitation for the big probe and increased cavitation efficiency for the small one (Fig. 5).

In short, an optimum of pressure is achieved due to opposite effects of hydrostatic pressure: a reduction of the number of cavitation bubbles due to a higher cavitation threshold, but a more violent bubble collapse. This optimum pressure is both *US* power and intensity dependent.

3.3. Optimal pressure under adiabatic sonication

Based on isothermal results, Le *et al*. [26] searched optimal values of hydrostatic pressure under adiabatic *US* in the 1 - 5 bar range at a given *ES* value, but for different P_{US} (100 - 360 W) and probe sizes. Results are shown in Fig. 6 where same *ES* (50000 kg/kg_{TS}) but different treatment durations were applied. This should however not much change the location of the optimum pressure, only the final corresponding DD_{COD} value (for instance increased from 60 % to 66 % at 360 W when after 33 min of *US*, the solution was let on stirring up to 78 min, to match the duration of the 150 W experiment). Note also that data of Fig. 6 do not correspond to the same final temperature.

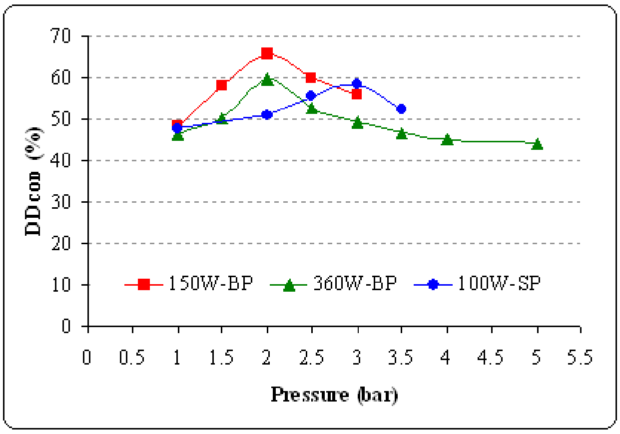


Figure 6. Effect of pressure on DD_{COD} under adiabatic sonication for different combinations of P_{US}-probe sizes: ES = 50000 kJ/kgTS, F_S = 20 kHz, secondary sludge with TS = 28 g/L [26].

Surprisingly, in adiabatic conditions, the same optimum pressure of 2 bar was obtained with the same probe (*BP*) at different P_{US} (150 and 360 W) while an increase would be expected at higher power according to isothermal data (section 3.2). The respective evolution of optimal pressure *vs*. P_{US} is complex in adiabatic condition and somewhat different with respect to isothermal case as the result of opposite effects of *T* on cavitation intensity and thermal hydrolysis. As observed, optimum pressures found under isothermal *US* were shifted differently depending on *T* profiles: slight increase at the moderate *T* resulting from 100 W adiabatic *US* with *SP* (from 2.5 bar -Fig. 3b- to 3 bar -Fig. 6), but a decrease at extreme *T* found at 360 W with *BP* (from 3.5 bar -Fig. 4a- to 2 bar -Fig. 6). This result was not expected and would deserve more analysis based on single cavitation bubble dynamics at high pressure and high *T*.

3.4. Dependence of hydrostatic pressure effect on sound frequency

The same *ES* of 35000 kJ/kg_{TS} was applied using the 12 kHz sonicator with P_{US} of 150 and 360 W through the big probe under pressure. Based on results at 20 kHz, the pressure range 1-4 bar was more carefully investigated with closer intervals of pressure: 0.25 bar. Results are presented in Fig. 7 [22].

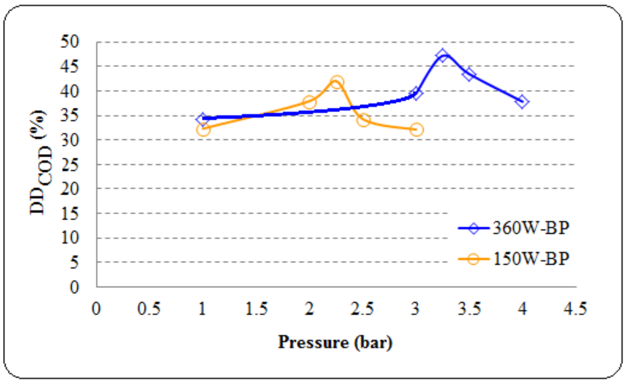


Figure 7. Effect of hydrostatic pressure on DD_{COD} of secondary sludge for different P_{US}: *BP*, *ES* = 35000 kJ/kg_{TS}, F_S = 12 kHz, *TS* = 28 g/L, and *T* = 28 ° ± 2C [22].

As previously found at 20 kHz (see § 3.2), the optimum pressure shifts when increasing I_{US}. Besides, the location of this optimum seems to be independent from sound frequency in the restricted investigated range: 2 bar at 150 W and 3.5 bar at 360 W (using 0.5 bar intervals) for 20 kHz as compared to 2.25 bar at 150 W and 3.25 bar at 360 W (0.25 bar intervals) for 12 kHz sonicator.

4. CONCLUSIONS

The effect of hydrostatic pressure on sludge sonication disintegration was studied in recent years and reviewed in this work. As far as sufficient acoustic intensity was provided, an optimum pressure (> 1 bar) was found due to an increase in both cavitation threshold and cavitation intensity when increasing pressure. While the effect of I_{US} on DD_{COD} was minor at atmospheric pressure, it was found to be much higher under convenient pressure. The most effective isothermal *US* would be high P_{US}, low F_S, convenient pressure, and adequate *TS*. Besides, positive effect of pressure associated with high P_{US} adiabatic *US* was also found. Interestingly, the optimum pressure could be affected by *T*. Concerning disintegration, a slight increase was obtained at moderate *T*, mainly due to higher numbers of cavitation bubbles, then a decrease at extreme *T* due to the less violent collapse of cavitation bubbles containing too much vapor. The major result was that the location of the optimal pressure depends on $P_{US,}$ I_{US} (or probe size), and *T*, but not on *ES*, F_S, nor sludge type. Such an important result would have to be checked in other *US* applications. In general, sludge disintegration efficacy was significantly improved by sonication at the optimum pressure as compared to that at atmospheric pressure, especially at low *ES*, leading to a potential of energy input savings in sludge sonication pretreatment, but also in most of ultrasound assisted processes (since the energy to pressurize the solution to the corresponding moderate pressure levels is much lower than the observed energy savings).

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TÓM TẮT

TỔNG QUAN ẢNH HƯỞNG CỦA ÁP SUẤT THỦY TĨNH LÊN HIỆU QUẢ TIỀN XỬ LÍ BÙN THẢI BẰNG CÔNG NGHỆ SIÊU ÂM

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Liên quan đến tiền xử lí bùn thải bằng công nghệ siêu âm, thay đổi áp suất thủy tĩnh sẽ thay đổi điều kiện cộng hưởng của bong bóng cavitation và có thể dẫn đến điều kiện cộng hưởng của hệ thống, theo đó là sự gia tăng tốc độ và năng suất của phản ứng. Tuy nhiên, hầu như tất cả các thí nghiệm siêu âm đều được thực hiện ở áp suất không khí. Ảnh hưởng của áp suất thủy tĩnh đến việc phân rã bùn thải mới được nghiên cứu trong những năm gần đây. Nghiên cứu này nhằm mục tiêu tổng quan ảnh hưởng của áp suất đến hiệu quả tiền xử lí bùn thải bằng công nghệ siêu âm ở các điều kiện khác nhau. Kết quả quan trọng của nghiên cứu là sự phụ thuộc của áp suất tối ưu vào P_{US}, I_{US} (hay kích thước đầu dò siêu âm) và nhiệt độ; không phụ thuộc ES, F_S cũng như loại bùn thải. Một cách tổng quát, hiệu quả phân rã bùn thải được cải thiện đáng kể khi siêu âm trong điều kiện áp suất tối ưu, đặc biệt ở ES thấp, mở ra tiềm năng to lớn trong việc tiết kiệm năng lượng không chỉ đối với công nghệ tiền xử lí bùn thải mà còn với hầu hết các quá trình ứng dụng siêu âm nói chung.

Từ khóa: áp suất thủy tĩnh, phân rã bùn thải, tiền xử lí bùn thải, siêu âm, tiền xử lí bằng siêu âm, bùn thải hoạt tính.