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Analysis of Energy Demand in the Process of Continuous and Pulse Sonication of Sewage Sludge

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1. Introduction

The problem of disposal and management of sewage sludge has been and is still valid. The increasing number of them requires the use of more and more efficient devices that meet certain standards, thus affecting the greater financial outlay. For these reasons, various methods are being sought to intensify the stabilization and drainage process. One of the known methods that helps to neutralize sewage sludge is ultrasonic disintegration. Depending on the parameters used, this method may have a coagulating or dispersive effect on the floc structure. It is a process that can be used at various stages of wastewater treatment.

The process of disintegration consists in the decomposition of solids contained in sewage sludge. Flocs are formed by various microorganisms, mainly bacteria and organic and inorganic matter. With the disintegration process, microorganism cells are decomposed, which leads to the release of intracellular fluids. This allows for easy removal of organic compounds that are contained in the cells during further processes of biological treatment of waste and processing of sewage sludge (Zhang et al. 2017, Guan et al. 2016, Grosser 2017). Disintegration enhances the decomposition of organic substances which are contained in the sludge and accelerates the process of transformation into biogas while reducing the final amount of sludge to be managed (Zawieja 2016, Gonze et al. 2003).

Disintegration of sewage sludge can be performed using various technologies. Methods differ from each other in the agent used for disintegration. Accordingly, they can be divided into mechanical, thermal, biological and chemical methods, freezing, oxidation and the ultrasonic method (Zhang et al. 2017, Zhou et al. 2014, Chang et al. 2001).

The elastic medium in which ultrasounds propagate can be liquids, gases and solids. Each medium differs from each other in their structure and velocity of wave propagation, whereas the mechanism of generation and propagation of the wave is the same. The effect of elastic wave with organic matter is particularly affected by the wave length and the process can occur in various manners. The use of the ultrasound field offers opportunities for generating processes with varied character, such as coagulation, agglomeration and fragmentation (Zielewicz 2016, Wolski et al. 2012, Feng et al. 2009).

Wave length and wave frequency represent the basic parameters used for the description of the ultrasound waves. The first parameter, i.e. wave length, depends on the medium where the process occurs (Zhang et al. 2008). The relationship between wave length and frequency can be defined by the equation:

$$\lambda = \frac{v}{f}, m \tag{1}$$

where:
υ – velocity of ultrasound wave propagation in the medium, m/s,
f – vibration frequency, Hz.

The longest ultrasound wave can be observed in solids, whereas the shortest waves propagate in gases.

The characteristic energy values of the ultrasound field determine transfer of energy through acoustic wave. Energy transported over a time unit is defined as acoustic power. If this energy is related to the unit of volume V of the sonicated medium, it is termed energy density. Density of energy stream is defined as energy per unit of area of the surface S which is perpendicular to the direction of wave propagation (Zielewicz 2016, Bień et al. 2015, Zhou et al. 2017).

According to Śliwiński (Śliwiński 2001), the acoustic field can be described by energy values that describe transport of energy through waves. The amount of energy which is transported by the acoustic waves over time of 1 s per area of the surface which is perpendicular to the direction of wave propagation is termed sound intensity. It is given by the equation:

$$I = \frac{N}{S} \tag{2}$$

where:
N – power transported by the waves, W,
S – surface of wave propagation, m^2.

The application of the ultrasonic field is connected with incurring some energy expenditure, the amount of which depends on the intensity of the field and the duration of the sonification. Therefore, the aim of the research was to determine the amount of energy introduced into the system depending on the wavelength (intensity) used, the time of exposure of the UD field and the type of process (continuous and pulsed). The research was preliminary (basic), therefore their scope was limited. In order to determine the effect of disintegration on the ability to drain, only the capillary suction time test was performed. Disintegration carried out periodically was limited to two intensity values (2.2 and 3.2 W/cm^2), and three exposure times (10, 30 and 60 seconds).

2. Methodology

The sewage sludge for the examinations was sampled from processes of treatment of residential waste water. The samples were taken after the process of anaerobic stabilization but before the process of dewatering and polyelectrolyte station. Dry matter content was 21.2 g/dm^3, whereas initial hydration was 97.88%. Dry mass content and initial hydration of sludge was determined based on the standard PN-EN-12880. Continuous disintegration was conducted using the energy of ultrasound field with intensity of 1.6, 2.2, 2.7, 3.2, 3.8 W/cm^2, with the wave length of 7.88, 15.77, 23.65, 31.54, 39.42 μm, respectively. Sonication of the sludge samples was conducted under static conditions for the period of 2, 5, 10, 20, 30, 45, 60 and 120 seconds. Periodical disintegration of sewage sludge was performed using ultrasound field energy with intensity of 2.2 and 3.2 W/cm^2, for 10, 30 and 60 seconds. The process of sewage sludge sonication used ultrasound processor Sonics VCX-1500 with maximal power output of 1500 W. Frequency of ultrasound field vibration was 20 kHz whereas maximal wavelength for the amplitude of 100% was 39.42 μm. The device is used to transform electricity into mechanical energy supplied to the titanium tip in the form of wave. The amount of energy supplied to the system was read after each measurement. Volume of the samples exposed to ultrasound field was 100 cm^3.

Simultaneously to the examinations aimed at the determination of the amount of energy supplied to the system, the capillary suction time (CST) was also determined. Capillary suction time of the fermented sonicated sludge was 436 seconds. Capillary suction time was measured using the Baskerville and Galle methodology, which is based on the measurement of time of transition of frontal boundary layer of filtrate as a result of the effect of suction forces in the paper used (Whatman 17). The result presented in the study was time of absorption of the sludge by the filtration paper between the rings with diameter of 32 and 45 mm.

3. Results and discussion

The examinations were aimed to determine the amount of energy supplied to the system (sewage sludge) in the process of continuous pulse sonication. Simultaneously, dewatering capacity of the sludge conditioned with ultrasonic wave was determined based on the capillary suction time.

The analysis of the results obtained in the study demonstrated the increase in the demand of the energy with elongation of the time of exposure to the ultrasound field (Fig. 1). The value of the energy supplied in the case of the 2-second continuous exposure, with ultrasonic wave length of 7.88 μm was 140 J. The 5-time elongation of sonication time for the discussed wave length caused an over 6-time increase in the demand for energy (889 J). In the next examinations, energy demand increased proportionally to sonication time. In the case of 120-second exposure, the amount of energy supplied was 8985 J.

For other wave length values, the analogous relationships were obtained as in the case of the amplitude of 20%. With the wave length of 15.77, 23.65, 31.54 and 39.42 μm, the amount of energy supplied to the system also increased with sonication time. The highest value of the energy supplied (25108 J) was recorded for the highest wave length (39.42 μm) and exposure time of 120 s.

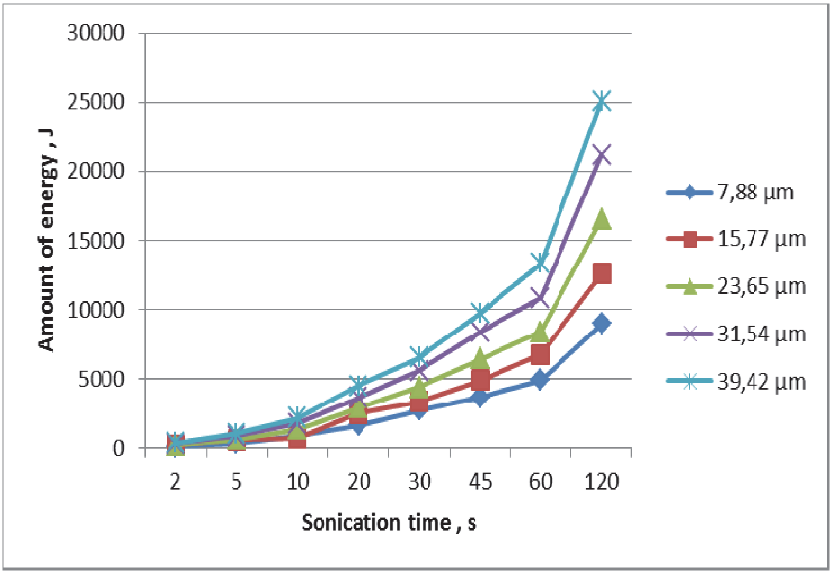

Fig. 1. Effect of continuous sonication time on the amount of energy supplied to the system depending on the ultrasound field wave length
Rys. 1. Wpływ czasu nadźwiękawiania ciągłego na ilość wprowadzonej energii do układu w zależności od zastosowanych długości fali pola ultradźwiękowego

The amount of the energy supplied to the system had an effect on dewatering capacity of sewage sludge, determined based on the capillary suction time. The lowest values of capillary suction time were obtained for sonication of sewage sludge with ultrasound field with wave length of 7.88 µm compared to four other amplitudes of the ultrasound field (Fig. 2).

With 2-second exposure, CST was 457 s and was insignificantly higher with respect to non-sonicated sludge. Elongation of sonication time led to the deterioration of the dewatering capacity expressed in higher values of capillary suction time. After 120 seconds, its value for the lowest amplitude (20%) was 1057 seconds. Higher values were found for other wave lengths and they were proportional to sonication time. With the highest wave length (39.42 µm) and sonication time of 120 seconds, the CST was 1323 s and was 3 times greater with respect to the non-sonicated sludge.

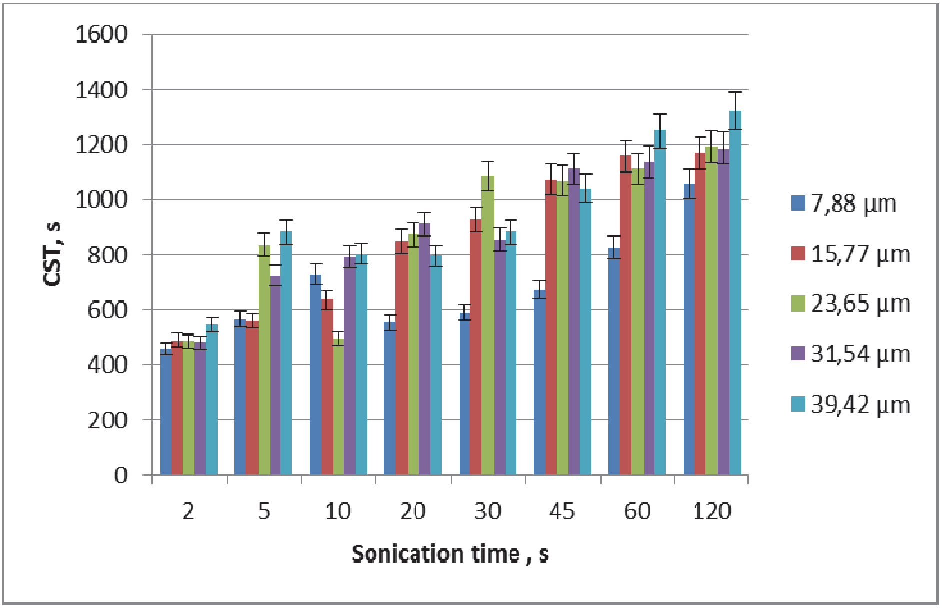

Fig. 2. The effect of continuous sonication time on capillary suction time depending on the ultrasound field wave length
Rys. 2. Wpływ czasu nadźwiękawiania ciągłego na wartości czasu ssania kapilarnego osadów ściekowych w zależności od zastosowanych długości fali pola ultradźwiękowego

The pulsating exposure led to the reduction in the amount of energy supplied to the system compared to the same parameters as in continuous sonication. Using the wave length of the ultrasound field of 15.77 and 31.54 µm, the amount of energy supplied to the system was, after 10 s, 1157 J and 1647 J, respectively (Fig. 3).

In the case of higher sonication time (60 s), the amount energy supplied to the system was 5298 J (15.77 µm) and 8967 J, respectively (31.54 µm). These values were lower than the amount of energy supplied continuously. The differences in the values of the amount of energy at the wave length of 31.54 µm was, after 10 minutes of exposure: 130 J; after 30 minutes of exposure: 1103 J; after 60 minutes of exposure: 1853 J.

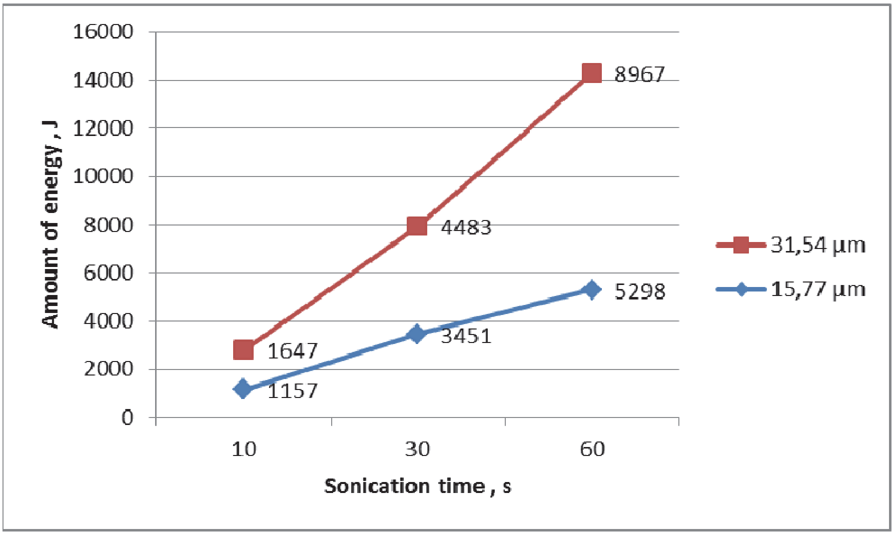

Fig. 3. Effect of pulse sonication time on the amount of energy supplied to the system depending on the ultrasound field wave length
Rys. 3. Wpływ czasu nadźwiękawiania pulsacyjnego na ilość wprowadzonej energii do układu w zależności od zastosowanych długości fali pola ultradźwiękowego

Lower energy supplied to the system during pulse sonication led to lower capillary suction times (Fig. 4). Improved dewatering capacity is connected with lower dispersion of sludge flocs and, consequently, clogging the pores in the filtration partition (Whatman 17). Furthermore, CST after 10 minutes of ultrasound exposure for the wave length of 15.77 µm was 623 seconds, whereas for the wave length of 31.54 µm, this value was 772 s. After 60 seconds of sonication, these values rose to 1041 s (15.77 µm) and 933 s (31.54 µm).

Changes in capillary suction time were correlated with changes in sludge structure caused by disintegration with exposure to ultrasound field. Non-conditioned sludge was characterized by the compact and homogeneous structure, without the likelihood of observation of free water (Fig. 5a). During exposure of the sludge to ultrasound field, single clusters of sludge flocs were observed, with zones of free water (Fig. 5b). The sludge flocs in the vision field were extended. The ten-day fermentation process caused homogenization of the structure observed (Fig. 5c). Flocs with free water were mixed, forming a uniform mass with individual clusters of the sewage sludge.

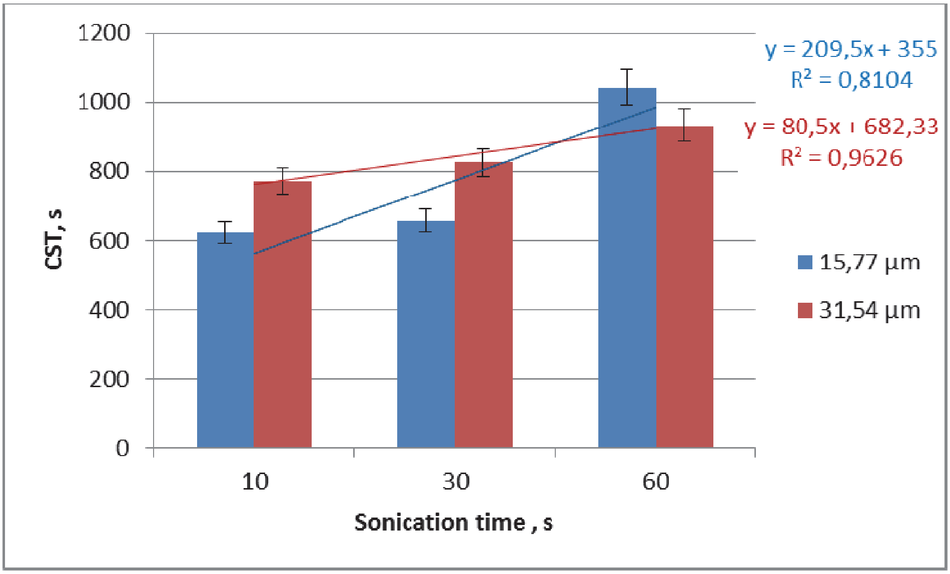

Fig. 4. The effect of pulse sonication time on capillary suction time depending on the ultrasound field wave length

Rys. 4. Wpływ czasu nadźwiękawiania pulsacyjnego na wartości czasu ssania kapilarnego osadów ściekowych w zależności od zastosowanych długości fali pola ultradźwiękowego

a) b) c)

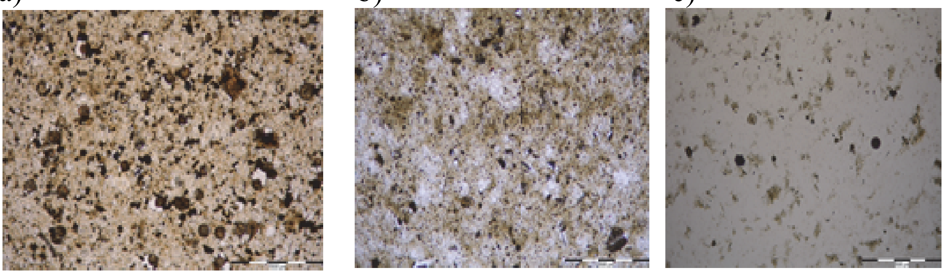

Fig. 5. Sewage sludge structure: (a) non-conditioned sewage sludge; (b) sewage sludge initially conditioned with ultrasound field; (c) sewage sludge initially conditioned with ultrasound field on the 10th day of fermentation

Rys.5. Struktura osadów ściekowych; a) niekondycjonowanych osadów ściekowych; b) wstępnie kondycjonowanych polem ultradźwiękowym;
c) wstępnie kondycjonowanych polem ultradźwiękowym w 10 dniu fermentacji

4. Conclusions

The study evaluated the amount of energy supplied to the system depending on the wave length and sonication time. Analysis also concerned the effect of the adopted methodology on capillary suction time. The examinations revealed the amount of energy generated with the increase in time and ultrasonic wave length. Sonication also led to the increase in capillary suction time. These relationships were observed in the case of both continuous and pulse sonication. During pulse sonication and the same parameters, lower amount of energy was supplied compared to the continuous ultrasound disintegration. The disintegration carried out in a pulsating manner influenced the smaller dispersion of sludge flocs, which ultimately had less influence on clogging of the filtration partition and obtaining lower values of the capillary suction time.

The results obtained in this study lead to the following final conclusions:

1) ultrasound field intensity determines the amount of energy supplied to the system. The increase in intensity and time of exposure to the ultrasound field causes an increase in the amount of energy supplied to the system,
2) amount of the energy supplied during the process of ultrasonic disintegration to sewage sludge impacts significantly on the value of capillary suction time. Its value of 1323 s, was the highest for the use of ultrasound field with intensity of 39.42 µm and sonication time of 120 s,
3) pulse sonication leads to a lower amount of energy generated. For the sonication time of 60 s and wave length of 31.54 µm, the amount of energy supplied through pulse sonication was 8967 J, whereas this value for continuous sonication was 10820 J.

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Zapotrzebowanie energetyczne w procesie ciągłej i pulsacyjnej sonifikacji osadów ściekowych

Streszczenie

Jednym ze sposobów kondycjonowania osadów ściekowych jest zastosowanie energii pola ultradźwiękowego. W wyniku jego działania w zależności od zastosowanych parametrów (natężenia pola UD, czasu działania) może dojść do koagulacji lub dyspersji kłaczków osadowych. Ilość dostarczonej energii do układu wynika z czasu działania i natężenia pola ultradźwiękowego.

Celem prowadzonych badań było określenie ilości wprowadzonej energii w zależności od czasu działania i natężenia energii pola ultradźwiękowego, oraz jego wpływu na ocenę efektywności odwadniania wyrażoną czasem ssania kapilarnego.

Jako substrat badań zastosowano przefermentowane osady ściekowe, które poddano działaniu pola ultradźwiękowego o natężeniu 3,8, 3,2, 2,7, 2,2, 1,6 $W \cdot cm^{-2}$ (co odpowiadało amplitudą 100, 80, 60, 40, 20%). W badaniach przyjęto czas sonifikacji z przedziału od 2 do 120 s. Na podstawie przeprowadzonych badań odnotowano wzrost zapotrzebowania na energie oraz wydłużenie czasu ssania kapilarnego wraz ze wzrostem amplitudy i czasu ekspozycji pola UD.

Abstract

One of the ways of sewage sludge conditioning is the use of ultrasonic field energy. As a result of its operation, coagulation or dispersion of sludge flocs may occur depending on the parameters used (UD field strength, operating time). The amount of energy supplied to the system results from the operating time and intensity of the ultrasonic field.

The purpose of the research was to determine the amount of energy introduced depending on the time and intensity of the ultrasonic field energy and its effect on the evaluation of the dehydration efficiency expressed by the capillary suction time.

Fermented sewage sludge was used as the substrate for the study, which was subjected to an ultrasonic field of 3.8, 3.04, 2.28, 1.52, 0.75 $W \cdot cm^{-2}$ (corresponding to amplitude 100, 80, 60, 40, 20%). The sonication time was from 2 to 120 s. On the basis of the research, the increase in energy demand and the increase of the capillary suction time with increasing amplitude and time of exposure of the UD field were recorded

Słowa kluczowe:
osady ściekowe, energia, nadźwiękawianie, czas ssania kapilarnego

Keywords:
sewage sludge, energy, sonication, capillary suction time