ARCHITECTURE CIVIL ENGINEERING ENVIRONMENT
The Silesian University of Technology No. 1/2008

ULTRASONIC DISINTEGRATION OF EXCESS SLUDGE BEFORE ANAEROBIC STABILISATION

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Received: 26.11.2007; Revised: 10.01.2008; Accepted: 30.01.2008

Abstract

The ultrasonic disintegration of sewage sludge is a new technique employed to improve sludge properties before its biochemical stabilization as a consequence of cells disruption. The effects of the disruption can be assessed by the tests determining the disintegration level such as: microorganisms condition, soluble COD in sludge supernatant, particle structure and others. In the present investigation we accepted the indicators defined as the increment in COD concentration for the sludge liquid phase after ultrasonic treatment. Two kinds of sludge collected in a municipal wastewater treatment plant were disintegrated using ultrasonic washers of frequency range 20-40 kHz and power range 90-500 W. The effect of ultrasonic treatment time (from 1 minute to 1 hour) and sludge layer height over the emitter on disintegration indicators was assessed. We determined the characteristics of ultrasonic field such as the dose of ultrasounds, intensity and energy consumption. Analyzing the results we can state that in order to obtain efficient disintegration in the tested washers, the doses of D_{GD} >0,6 kWh/m^2 and I_{GD}>0,75 W/cm^2 were needed – this implied the energy consumption of $E_{(m3)}$ > 6,4 kWh/m^3.

Streszczenie

Dezintegracja ultradźwiękowa osadów ściekowych jest technika nową, która prowadzi do poprawy właściwości osadu dla jego biochemicznej stabilizacji dzięki zniszczeniu komórek mikroorganizmów. Efekty rozbicia komórek mogą być określane za pomocą testów opisujących poziom dezintegracji jak: kondycja mikroorganizmów, ChZT substancji rozpuszczonych w cieczy osadowej, struktura cząstek i inne. W przedstawionych badaniach. zastosowano wskaźniki zdefiniowane jako wzrost ChZT substancji rozpuszczonych w fazie ciekłej osadu po nadźwiękawianiu. Dwa rodzaje osadów pochodzących z oczyszczalni miejskiej poddawano dezintegracji ultradźwiękowej, w myjkach ultradźwiękowych o częstotliwościach 20-40 kHz i mocach 90-500 W. Badano wpływ czasu nadźwiękawiania (od 1 min do 1 h) i grubości warstwy osadu nad emiterem na efekty dezintegracji. Określono wielkości charakterystyczne pola ultradźwiękowego jak częstotliwość dawkę emitowaną oraz zużycie energii. Analizując uzyskane wyniki stwierdzono, że uzyskanie efektywnej dezintegracji w stosowanych myjkach wymagało dawki energii ultradźwiękowej D_{GD} > 0,6 kWh/m^2, I_{GD} > 0,75 W/cm^2 co oznacza zużycie energii $E_{(m3)}$ > 6,4 kWh/m^3.

Keywords: **Ultrasonic disintegration; Sewage sludge; Disintegration indicators; Energy consumption; Sonolysis.**

1. INTRODUCTION

The effects involving the changes of medium caused by active reaction of ultrasonic field can be of different character, depending on the parameters of the field and physicochemical parameters of the medium subjected to ultrasonic treatment.

The most fundamental factors of attractiveness involving various application potentials of ultrasounds, both with respect to research aspect and particular industrial installations are as follows:

- the possibility to obtain changes without the necessity to apply additional components, e.g. chemical agents,
- ultrasonic treatment carried out in low or medium temperatures and pressure, which considerably simplifies the construction and operation of reactors and auxiliary installations,
- possible air tightening of the installation [1]

The application of ultrasonic disintegration to the treatment of sludge is a new technique. There are already installations making use of ultrasounds for the treatment of excess sludge on a technological scale e.g. before methane fermentation in separated fermentation chambers [2, 3, 4, 5] but the technology of acoustic-mechanical disintegration of microorganisms' cells is still in the experimental phase.

2. QUANTITATIVE AND QUALITATIVE PARAMETERS OF ULTRASONIC DISINTEGRATION

Ultrasonic vibration propagates in the medium in the form of acoustic waves which have the following characteristic quantities: wavelength – λ, propagation velocity in a given medium – *c*, form of wave surface and vibration direction with respect to the direction of wave propagation [6]. Vibration phases are repeated periodically in space every each wavelength and in time every each vibration period – *T*. The following relation is taking place between the enumerated parameters:

$$c = \lambda \cdot f = \lambda / T, \quad \text{(m/s)} \tag{1}$$

Wavelengths corresponding to the frequencies used most commonly in ultrasonic treatments, i.e. *f* within the range 10-100 kHz, have the values for water λ = 1.5 – 15 cm respectively.

All enumerated quantities are directly related to the parameters of the medium, and in particular, to its concentration – *ρ*, elasticity expressed by Young's modulus – *M* and acoustic impedance – *z*.

$$c^2 = M / \rho, \quad \text{(m}^2\text{/s}^2\text{)} \tag{2}$$

$$z = c \cdot \rho, \quad \text{(kg/m}^2\text{s)} \tag{3}$$

The ultrasonic wave is carrying a definite acoustic energy – *E* whose concentration – *W* in acoustic field of the volume – *V* has the following value:

$$W = E / V, \quad \text{(Ws/m}^3\text{)} \tag{4}$$

The amount of this energy carried in time unit is referred to as acoustic power of ultrasonic wave – *P* and is defined by the following expression:

$$P = E / t, \quad \text{(W)} \tag{5}$$

The intensity of ultrasonic wave – *I* is a vector quantity and it defines the amount of acoustic energy – *E* passing within time unit – *t* through the surface unit perpendicular to the direction of ultrasonic wave propagation. The value of wave intensity whose propagation rate in the medium is – *c* can be presented using the following equation:

$$I = W \cdot c = E \cdot c / V, \quad \text{(W/m}^2\text{)} \tag{6}$$

The portion of energy which is introduced to the area subjected to ultrasonic treatment *D* is expressed by the product of intensity and emission time – *t*:

$$D = I \cdot t = W \cdot c \cdot t = E \cdot c \cdot t / V, \quad \text{(Ws/m}^2\text{)} \tag{7}$$

In practical applications of ultrasonic treatment, the real parameters of ultrasonic field in the area of its reaction are very rarely defined, since their measurement is difficult and it requires both knowledge in the field of acoustics as well as specialist, expensive measurement equipment. The measurement of acoustic energy in laboratory conditions for research purposes can be carried out using the calorimetric method. Our investigation studies conducted for sludge revealed that the values of these parameters depend not only on frequency but also on the properties of sludge and geometric parameters of the area subjected to ultrasonic treatment, including the position of emitter with respect to sludge-table [7]. However, even on the semi-commercial scale, the calorimetric measurement of ultrasonic energy *E* is almost impossible. Therefore, to characterize the ultrasonic field, we decided to apply the methodology based on the determination of the output parameters of ultrasonic vibration source, for which we only need to know the electric parameters of the generator which are passed to the head of the ultrasonic emitter. More important parameters for the operation of disintegration facilities are those which bespeak the energy consumption of disintegration process as well as those which allow to determine the amount of energy E_G emitted to the area subjected to ultrasonic treatment needed to ensure a desired disintegration effect within an area of a definite volume. The amount of energy can be assumed as the amount corresponding numerically to the product of power P_G of electro-acoustic transformer and disintegration time – t_D. To ensure a desired effect, an appropriate dose of electroacoustic radiation – D_G should be introduced to the system; the dose can be also determined numerically as the product of the emitted intensity of ultrasonic wave – I_{GE} and disintegration time. I_{GE} and I_{GD} are respectively the values of output intensity of ultrasonic field with respect to the emitter's field and the field of the disintegrator's bath-tub, perpendicular to the emission direction, and A_E and A_D are respectively the fields of the emitter and bath-tub.

The amount of energy is emitted to a definite disintegration area of the volume – V_D, so the unit indicator, i.e. the energy per volume unit will be the right indicator to specify the amount of energy put into the disintegration process: $E_{G(m3)}$ (kWh/m^3).

The enumerated values characterize the disintegration tool, and their relation with the obtained effects of ultrasonic treatment process and their role in optimal designing of this process are the key problems concerning the implementation of sludge disintegration technology for the intensification of biological decomposition of organic substances.

2.1. Evaluation indicators of disintegration

The disintegration degree of cells can be described using a number of physicochemical and biological parameters [8]. The disruption of cell membranes leads to the killing of the microorganisms and to the liberation of intracellular chemical compounds to the liquid phase of the sludge. The annihilation ratio of cells can be therefore defined by the increase of chemical oxygen demand (COD_S = COD means centrifugal separation and filtering). COD_S of the dissolved fraction was determined after 30 min rotation of the sludge sample at 20 000 rev/min followed by filtering the obtained liquid through the 0.45 μm cellulose acetate filter [9]. Depending on the origin of sludge, the resistance to the mechanical damage of cell membranes of the microorganisms can be different and variable in time.

The literature on various disintegration methods of sludge provides different indicators of disintegration process elaborated by the authors [8, 9, 10, 11], but so far they have not been standardized. For the evaluation of sludge disintegration, it is useful to apply indicator K_{d2} defined as the ratio of COD increment of sludge liquid after ultrasonic treatment (ΔCOD_{SD}) to COD of the liquid which was not subjected to ultrasonic treatment (COD_{SN}):

$$K_{d1} = \Delta COD_{SD} / COD_{SN}, \quad \text{(n.d.)} \tag{9}$$

where:

K_{d1} – is an indicator of the increment in COD of supernatant after ultrasonic treatment, (n.d.)

$(\Delta COD_{SD}) = COD_{SD} - COD_{SN}$, (mg O2/dm$_{SN}$)

indexes: S – soluble, D – disintegrated, N – no disintegrated.

We can also define directly the multiplicity of the increment in COD concentration for the sludge after ultrasonic treatment:

$$K_{d2} = COD_{SD} / COD_{SN}, \quad \text{(n.d.)} \tag{10}$$

where:

K_{d2} – is an indicator of the multiplicity of the increment in COD of supernatant after ultrasonic treatment, (n.d.)

The results concerning the disruption of bacteria walls can be also defined using the tests determining the level of oxygen consumption for physiological needs of microorganisms. Since a considerable part of excess sludge is made up by oxygen microorganisms of activated sludge, the rate of oxygen consumption – breathing activity, can be applied to determine the level of ultrasonic disintegration. When all oxygen bacteria present in the sludge are annihilated, the rate of oxygen consumption by the sludge will be close to zero and the disintegration level will reach 100% [11].

In their investigation studies, the authors have found that short reaction times of ultrasounds can bring about the increase in the breathing activity of microorganisms, and only after a longer time of ultrasonic treatment and consequently after the increase in energy dose with respect to volume unit, the breathing activity disappeared [12]. Due to the disintegration of primary texture of the floccules of excess sludge, we can also observe the decrease in the average size of sludge particles after ultrasonic treatment. Therefore, the estimation of sludge disintegration can be carried out by monitoring the amount and size of particles [13]. In the initial phase of disintegration, the rise in the number of microorganisms can be observed, which is taking place during the disintegration of floccules into single cells. Then, after a longer ultrasonic treatment, the number of microorganisms are decreasing, since the cells have been annihilated [14]. The break up level of the solid phase of the sludge can be also estimated by investigating the susceptibility changes of the sludge subjected to disintegration to water return ability measured by the filtration test CST (s) (capillary suction time). This estimation type is based on the known relation which reads that the filterability of sludge is decreasing with the rise of dispersion degree of solid phase, and hence the drop of particle size after the disintegration brings about the rise of CST [15, 16, 17]. The multiplicity of CST rise of sludge subjected to ultrasonic treatment with respect to the sludge not subjected to ultrasonic treatment can be therefore used to estimate the mechanical, dispergating effect of ultrasounds' reaction.

$$K_{d3} = CST_{SD} / CST_{SF}, \quad \text{(n.d.)} \tag{11}$$

where:

K_{d3} – an indicator of the dispergating effect after ultrasonic treatment, (n.d.)

As a measure of disintegration level in the present investigation studies, we accepted the indicator defined as K_{d2}.

3. METHODOLOGY OF INVESTIGATION

The range of investigation studies involved the determination of the influence of generated power, geometrical parameters of ultrasonic treatment chamber and ultrasonic treatment time on the effects of ultrasonic disintegration obtained in excess sludge. The main objective of the studies was to examine the reaction of ultrasonic field produced by disintegrators designed as ***ultrasonic washers*** with various power and geometrical parameters of the disintegrator's bath-tub. The sludge samples were subjected to ultrasonic treatment using disintegrators of various construction whereof the majority emitted the frequency of a range of 20 - 25 kHz, and one of them 40 kHz.

The frequency of 20 kHz was estimated to be the most favourable with respect to the preparation of sewage sludge, basing on the analysis from the previous test cycles, whereof results had been presented at conferences and in scientific journals [17, 18]. The change of frequency within the range 20-25 kHz has no considerable influence on the changes of disintegration effect, whereas the following parameters were changed considerably: volume, output power of washers (the range of 90-500 W), disintegration times and height of the sludge layer over the emitter (the emitters in washers are installed in the bottom of an ultrasonic treatment chamber – bath-tub). The list of parameters of the disintegration process is presented in Table 1*. The tests were carried out in static conditions, using disintegration times t_D within the range from 1 minute to 1 hour. The dimensions of the emitters and ultrasonic treatment chambers allowed to carry out the treatment of relatively high volumes of samples (as compared to laboratory tests), and they also allowed to support the ultrasonic treatment with stirring.

* The disintegration equipment was borrowed from "Intersonic" – a firm in Olsztyn.

Table 1.
Parameters of disintegration appliances

Number of ultrasonic washers	Frequency of ultrasonic washer f	Number of emitters	Volume of washer V_D	Surface of washer A_D	Power of generator P_G	Intensity of ultrasonic field I_{GD}
n.d.	kHz	n.d.	dm^3	cm^2	W	W/cm^2
1	40	1	2,5	400	300	0,75
2	25	1	5,0	230	90	0,72
3	20	1	7,8	800	600	0,76
4	22	6	12,5	1250	500	0,40

Table 2.
Parameters of ultrasonic treatment process and disintegration effects described by the indicator K_{d2} for all washers and both sludge (K I and K II)

C_0	P_G	t_D	f	E_G	h	V	$E_{G(m3)}$	I_{GE}	I_{GD}	$D_G=I_{GD}*t_D$	A_E/A_D	K_{d2}
%	W	min.	kHz	kWh	cm	dm^3	kWh/m^2	W/cm^3	W/cm^2	kWh/m^2	n.d.	n.d.
3,6	600	5	20	0,055	10	7,8	6,4	25,0	0,76	0,63	0,12	3,5
3,6	300	5	40	0,025	9,5	1,0	25	12,5	0,75	0,62	0,24	1,6
3,6	90	5	25	0,008	9,5	2,2	3,6	3,75	0,72	0,60	0,10	2,6
3,5	500	5	22	0,042	10	12,5	3,4	3,50	0,40	0,33	0,11	1,7

With respect to overall dimensions and emitted field intensity, the tested appliances corresponded with the appliances used on a technical scale for ultrasonic treatment of various materials, but which were adapted to the treatment of sewage sludge.

The investigation studies dealt with excess sludge after the process of integrated removal of biogenic compounds in A2/O technology, collected from a big municipal wastewater treatment plant at which anaerobic stabilization of mechanically thickened sludge is carried out. The samples collected at different times only slightly differed in the concentration of dry solids (hydration) and content of organic compounds. The sludge samples were marked with symbols **K I** (C_0 = 3,6%) and **K II** (C_0 = 3,5%) (both were thickened on a mechanical appliance with the aid of polyelectrolyte) and they had a very fine structure.

The tests involved the determination of the direct effect of disintegration measured by the multiplicity of COD increment of liquid over the sludge after ultrasonic treatment, and expressed by means of the disintegration indicator K_{d2} defined above (equation 10).

4. RESULTS AND DISCUSSION

The application of high volume washers, with emitters installed in the bottom, brought about a situation in which parameters such as retention time and layer height of sludge over the emitter played the most relevant role. Both of these parameters are directly connected with the amount of energy which should be emitted to the system to obtain satisfactory results of disintegration.

The influence of time increase applied to ultrasonic treatment process on the effects of ultrasonic disintegration carried out in non-flow systems was observed for all samples of sludge. The longer the time of ultrasonic treatment was, the higher K_{d2} was defining directly the multiplicity of COD increment after the disintegration. It has been found that there is a necessity to carry out the disintegration of sludge over time periods several times longer than it was in the tests carried out on a laboratory scale, which is obvious since in order to obtain a similar dose of ultrasonic emission, with comparable power of the appliances, the amount of energy introduced to the system could be increased principally through the prolongation of the emission time.

The disintegration parameters can be divided into ones which characterize the disintegration appliance: power, frequency, output intensity as the dimension function of (most frequently of the diameter) the emitter, and then the ones which depend on the way they are introduced into the medium, size and shape of transverse section of the area subjected to ultrasonic treatment, volume of this area and depth of emitter's position under the sludge-table, and finally into parameters which depend on the properties of the medium i.e. concentration, content of solid matter, content of organic substances, viscosity, elasticity and others. Table 2 presents some of the investigated parameters of ultrasonic disintegration which were compared to the obtained effects expressed by the disintegration factor K_{d2} with respect to the same emission time.

The testing of semi-technical disintegrators of the type of ultrasonic washer also showed that they did not allow to obtain considerable increment in COD if the sludge layer over the emitter was higher than 10 cm, even for the disintegrator's power comparable to the power applied in laboratory conditions (range 300-500 W).

The difference between the disintegration effects in the field just over the emitter (h = 1cm) and in the sample layer on h = 9.5 cm is huge. The value of K_{d2} for the time t_D = 3 min. (Fig. 1) or t_D = 4 min. (Fig. 2 and Fig. 3) of the sludge disintegrated on the thin layer over the emitter is corresponding to the value of this indicator for sludge after 15 min of ultrasonic treatment but with the layer 9.5 cm. For that reason, the mixing of sludge during the ultrasonic treatment with the high layer is very important and profitable. Stirring of the sludge (slow, at a rate of 50 rev/min) supports the disintegration process (Fig. 1) since, as it was observed, it helps to break up big floccules created with polyelectrolyte. Furthermore, the stirring helps to exchange the layers of the sludge which are directly subjected to the influence of the emitters.

With the same heights of layers and the same time of disintegration of the same sludge, the disintegration effect was dependent on the volume of sludge being subjected to ultrasonic treatment, even if the output intensity (I_{GE}) and energy consumption per volume unit ($E_{G(m3)}$) were comparable (Table 2). The results gathered in Table 2 also illustrate that there is a distinct influence of the energy dose on the disintegration effect with the frequencies close to 20 kHz, since the disintegration indicator K_{d2} was twice as low – 3.5 and 1.7 respectively, when the applied dose was almost twice as small, 0.63 and 0.33 kWh/m^2 respectively.

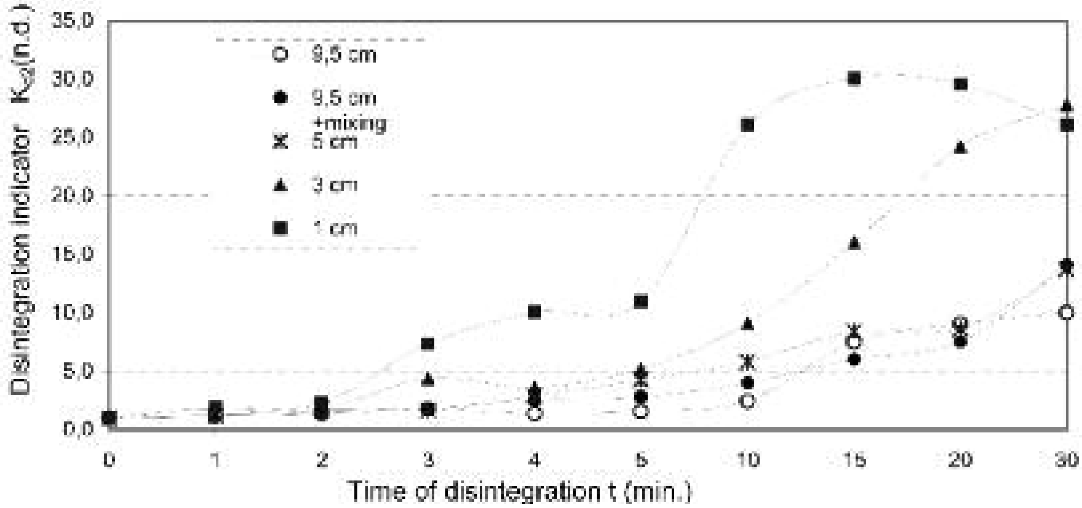

Figure 1.
Influence of sludge layer height over the emitter on disintegration indicator K_{d2} for sludge KI (C_0 = 3.6%) and ultrasonic washer No 1 (*f* = 40 kHz)

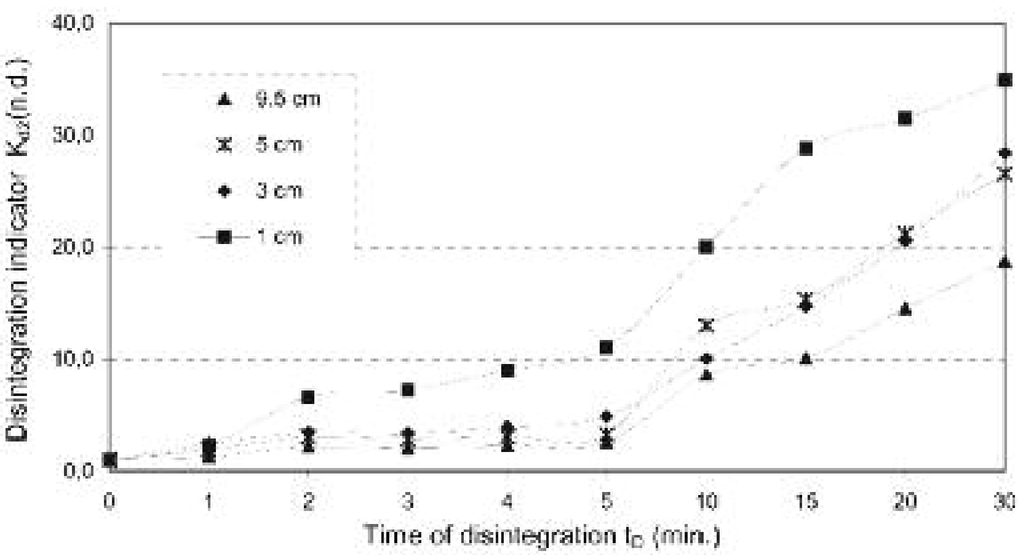

Figure 2.
Influence of sludge layer height over the emitter on disintegration indicator K_{d2} for sludge KI (C_0 = 3.6%) and ultrasonic washer No 2 (*f* = 25 kHz)

In view of several years of tests on the ultrasonic disintegration of sludge, we can observe that the disintegration effect is the function of many parameters, the most relevant ones in terms of process efficiency having been singled out. By far the highest unit consumption of energy was taking place with the ultrasonic treatment where the frequency of 40 kHz was applied, with the disintegration effect being the lowest, comparable to the one obtained for the frequency of 22 kHz (washer No 4) but with the dose of ultrasonic emission reduced by 50%. With the same heights of layers and the same time of disintegration t_D = 15 min. of sludge KI, the similar effect ($K_{d2} \approx 30$) was obtained in washer No 1 and No 2 (the results in Fig. 1 and Fig. 2) but the energy consumption for the disintegration in washer No 2 (25 kHz) was three times lower than for the disintegration in washer No 1 (40 kHz).

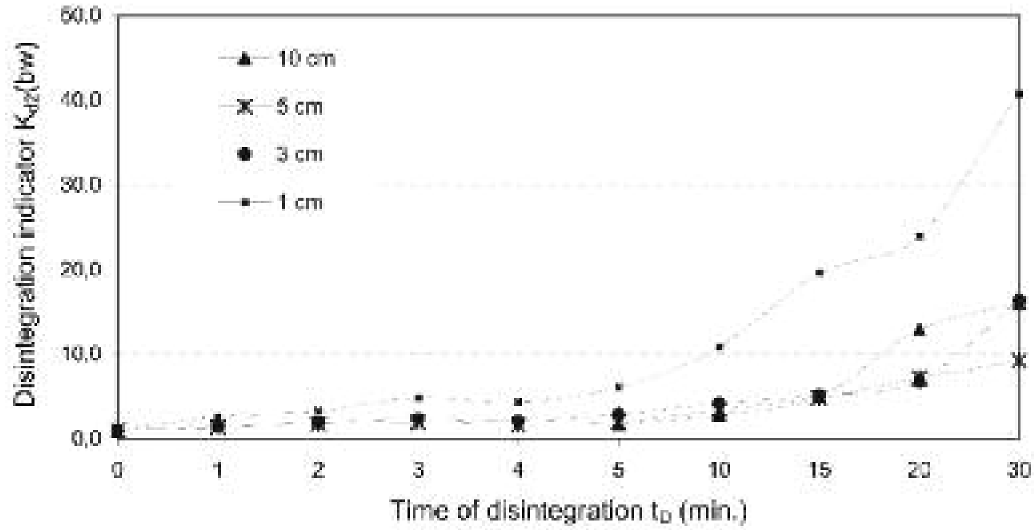

Figure 3.
Influence of sludge layer height over the emitter on disintegration indicator K_{d2}, for sludge KII (C_0 = 3.5%) and ultrasonic washer No 4 (f = 22 kHz)

5. CONCLUSION

Ultrasonic disintegration of excess sludge before the processes of biochemical stabilization results in the annihilation of the microorganisms of activated sludge and hence increases the susceptibility of the sludge to biodegradation. As a result of disintegration measured directly after ultrasonic treatment, we observe the rise in CODS in the dissolved form, being the result of the liberation of intercellular substances to sludge liquid (effect of sonolysis). The obtained effect depends on many factors and parameters of disintegration, and the search for optimum conditions for the process on a technical scale emphasizes a huge role of frequency and dose of ultrasonic energy. Both on the laboratory scale and semi-technical one the frequency of 20 kHz turned out to be the most efficient and most economical. Also the parameters characterizing the geometry of the disintegration chamber are very important, the immersion depth of the emitter in the sludge in particular. In the disintegrators of the washer design, having the emitter installed in the bottom, the depth of sludge layer should not be higher than 10 cm. In the non-flow appliance, it is also advantageous to apply stirring of suitable characteristic, ensuring the exchange of the sludge layer directly over the emitter.

In view of the observations, analyzing the results presented by the diagrams, we can state that in order to obtain efficient disintegration in the tested washers, a dose of D_{GD} > 0.6 kWh/m^2 (D_{GD} = 0.06 W/cm^2) with intensity I_{GD} > 0.75 W/cm^2 (both parameters were determined with respect to the surface area of bathtub) should be emitted. At the same time, these parameters correspond with such parameters of the emitted ultrasonic wave as frequency range of 20-25 kHz, and consumption energy indicator E_G(m^3) > 6.4 kWh/m^3 (0.0064 kWh/dm^3).

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