TRENDS IN INTENSIFICATION OF THE ANAEROBIC DIGESTION PROCESS AT MODERN WASTEWATER TREATMENT PLANTS

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ABSTRACT
The paper presents recent trends in solving sludge management problems at wastewater treatment plants. The problems are approached using advanced sludge processing and utilization methods and following, at the same time, principles of sustainable development and energy recovery. A relatively new technology, presented in this paper, is the pre-treatment of sludge process. This technology intensifies biogas production and improves quality of digested sludge. Based on the literature review, the methods used for sludge pre-treatment, before its anaerobic digestion, are described. Additionally, authors presented results of' their own experiments, performed on sludge samples taken from the Gdańsk WWTP (unit with biological nutrient removal and poorly working mezophilic sludge digestion).The objective of the study was to examine methods of preliminary sludge preparation, before its anaerobic digestion, to enhance the digestion process.

KEYWORDS
wastewater sludge; sludge treatment processes; anaerobic digestion; disintegration; biogas; VFA

INTRODUCTION

Advanced wastewater treatment plants, apart from providing a sufficient level of treatment for wastewater, have to recognize and assure an appropriate level of sludge management. That objective can be achieved by a substantial reduction of sludge volume, sludge stabilization and hygenization as well as its ultimate utilization.
Moreover, implementation of the principles of sustainable development obligates the users to introduce advanced methods that enable to recover some valuable products from sludge (Kurbiel et al., 2001).

Possibilities, associated with recovery and utilization of products obtained through sludge decomposition, deal mostly with anaerobic digestion of sludge, although some potential in this field may also be identified in anaerobic/aerobic sludge treatment processes. The paper focuses on the problems related with intensification of biogas production at wastewater treatment plants with biological nutrients removal, as well as on the improvement of digested sludge quality.

GENERAL DESCRIPTION OF ANAEROBIC SLUDGE DIGESTION

In the process of anaerobic sludge digestion 4 phases (fig.1) of decomposition can be identified. Each phase involves different bacteria cultures. They are:

hydrolysis bacteria
acid bacteria
acetates bacteria
methane bacteria

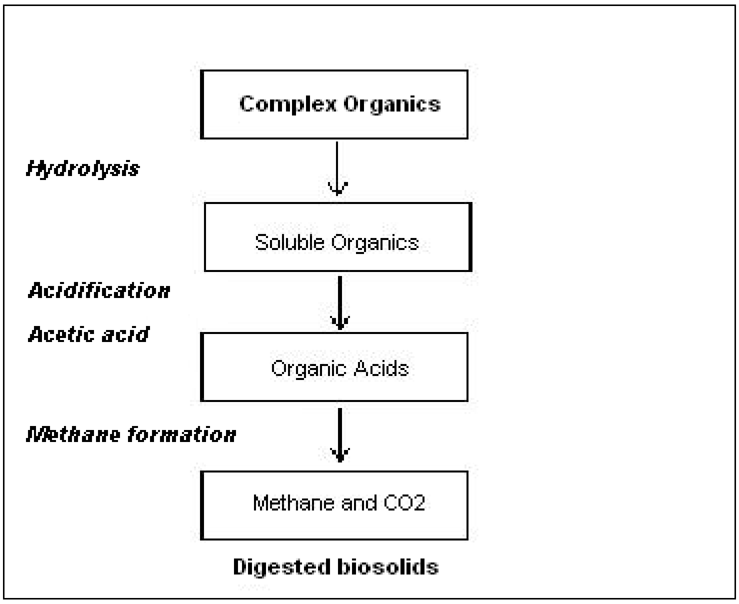

Figure 1. Process of anaerobic sludge digestion.

Optimization of the process is possible due to application of technologies, which are based on the knowledge of transformations mechanisms, conditions and reaction rates of specific processes. The process involves biochemical disintegration of substrates, carried out by the bacteria cultures that had been specified above.

Hydrolysis and acidification
Microorganisms of the 1st phase have the ability to hydrolyze (with their extra cellular enzymes) such high- molecular substrates as hydrocarbons, acids and proteins to simpler low molecular structures like glucose, glycerol, fatty acids and amino acids.

At the same time, particulate organic matter is solubilized. The products of hydrolysis are adsorbed by microorganisms, digested and broken down mostly to the form of acetic acid, propionic acid, butyric acid, hydrogen, alcohol, ammonium and hydrogen sulphide.

Hydrolysis is the limiting phase of the anaerobic sludge digestion since production of valuable egzoensymes by microorganisms can be inhibited by the substrate. The complete inhibition of the process takes place at pH<6.5 ((Henze M. et al., 1995).

Acetic acid phase
Bacteria responsible for production of acetic acid transforms such intermediate products like long chain fatty acids (lactic acid) and alcohols to the form of acetic acid, hydrogen, carbon dioxide and ammonium.

While digestion of sugars and amino acids proceeds quite rapidly and without major problems (is not inhibited by a low pH), the conversion of long chain fatty acids to acetic acid and hydrogen proceeds at a much slower rate. It is due to a much slower growth rate of bacterial cultures, which are sensitive to the low pH values and therefore may become inhibited by some reaction products..

Methane phase
Each species of methane producing bacteria is highly specialized and they contribute to decomposition of a selected group of chemicals, produced during the previous phases. Apart from hydrogen, carbon dioxide and acetic acid, some of bacteria can assimilate lower alcohols, formic acid and carbon oxide. Generation time for methanogenic bacteria is 2-5 days. Those bacteria are very sensitive to environmental changes; drop of pH below 6.0 or above 8.0 can inhibit their growth, which then becomes slower and more difficult. Likewise, too often fluctuation of temperature (more then 2^oC) can disturb the digestion process (Henze M. et al., 1995).

For some substrates, hydrolysis becomes the final phase of disintegration. It means that only some portion of sludge can be broken down to gaseous products. Other residual material is discharged together with supernatant from anaerobic environment and recycled back to the wastewater treatment line. There are also organic fractions of sludge, which are resistant to hydrolysis and do not undergo anaerobic digestion. It was found, that some activated sludge bacteria extracted from anaerobic/aerobic reactors have cell membrane resistant to hydrolysis and therefore, they are not susceptible to efficient digestion (Kurbiel et al., 2001).

TRENDS IN ANAEROBIC DIGESTION

The predominating tendency in the anaerobic digestion development is application of sludge disintegration methods to intensify methane and volatile fatty acids (VFA) production. As it was already stated, a preliminary hydrolysis phase is the limiting step in a digestion process. During this phase, particulate organics become solubilized and as such, they can serve as a substrate and an energy source for anaerobic bacteria, responsible for the process. It may be assumed, that the increased surface of the particles (due to their decomposition) could enhance the rate of hydrolysis. Therefore, the technology that can stimulate higher hydrolysis rates can also intensify both VFA production and methane digestion, since these processes are coupled. A simultaneous decrease of organic content in the digested sludge is also an important element of a sustained development principle.

In Figure 2 a layout of the advanced biological wastewater treatment plant with sludge anaerobic digestion was presented. In this layout, points of possible application of sludge disintegration methods were highlighted (Ried A. et al., 2002). The letters A – D indicate different possibilities of technological introduction of a disintegration phase. In each of these points, disintegration of either a part of the stream or a whole stream can occur. The most popular methods include disintegration of excess and recycled sludge as well as disintegration of floated and bulked sludge.

Placing disintegration ahead of the digestion process, results in a significant shortening of a digestion time and enhanced production of biogas. When disintegrating sludge is already digested to some degree (D), both higher gas production and organic matter decomposition can be expected (Ried A. et al., 2002).

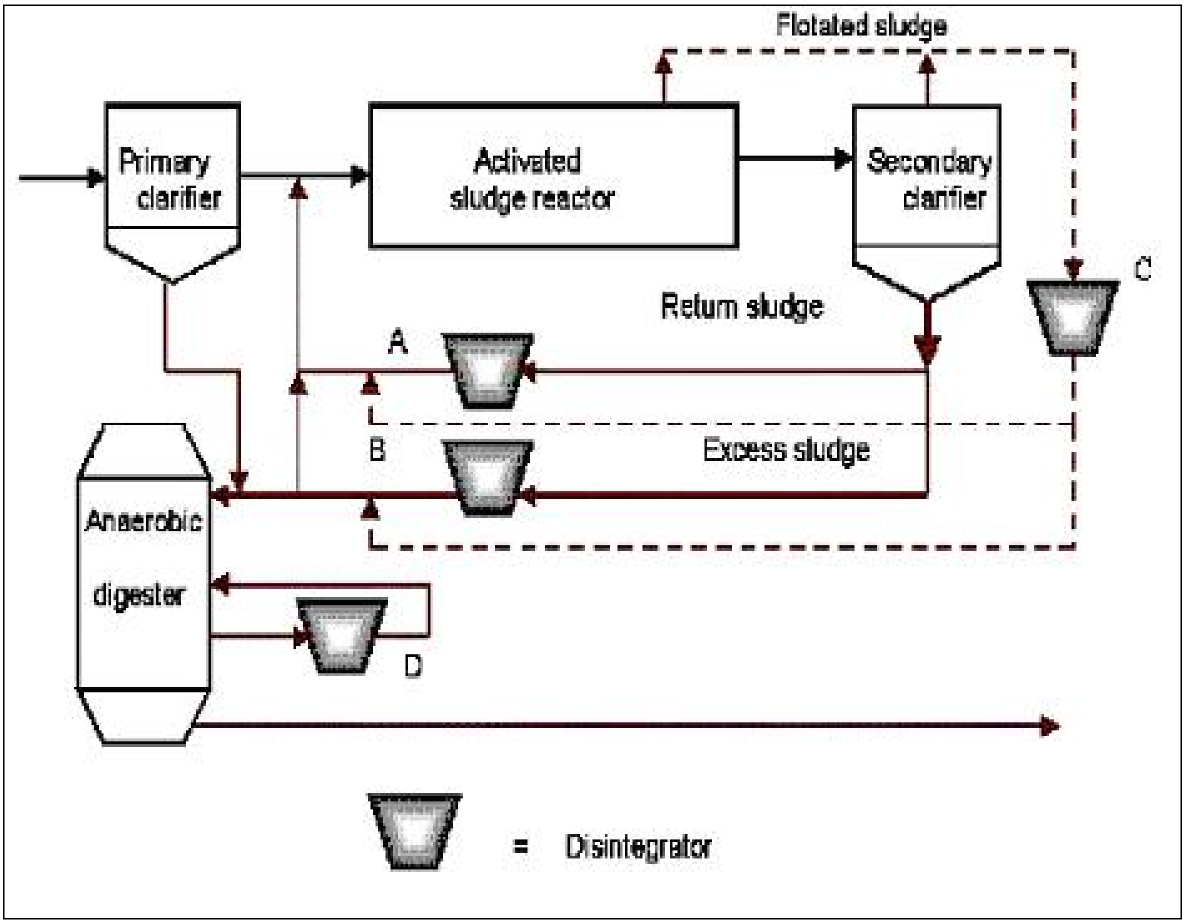

Figure 2. Areas of application of disintegration sludge.

The following disintegration methods have been investigated (mostly at experimental and pilot scales):

Thermal disintegration
During thermal hydrolysis, a substantial fraction of particulates can be separated and decomposed to a soluble and less complex form. During so called "subcritical wet oxidation" (van Veen et al.,2001) a complete destruction of organic fraction occurs at 374 ^{0}C (22,1 MPa). The process is still under investigation and one of its main constrains is recycle of soluble forms of nitrogen (mostly ammonium) with the produced VFA to biological reactors.

Another method of thermal disintegration is heating of the excess sludge to temperature above 150^{0}C for over 30 minutes. In this process, the disruption of activated sludge cell membranes and conversion of organics to a more readily digestible form occurs (Hobson, 1994).

Ultrasonic disintegration
Introduction of ultrasonic technology is quite a new approach in sludge processing. Especially low frequencies, in the range from 20 to 100 KHz, exhibit a strong destructive power. The experiments on disintegration of primary sludge (Tiehm et al.,1997), 1:1 mixture of primary and excess sludge (Quarmby et al.,1999) and excess sludge only (Zielewicz, 1997), showed that the process generates smaller sludge particles and enhanced production of VFA.

At a technical scale, Anglia Water has carried out the experiments at the WWTP in the US (Gotthardssoon, 2002). A disintegrating unit was mounted on the pipe, which transports sludge to the anaerobic digesters.
Energy consumption for the sludge disintegration with ultrasounds is approximately 0.3 kWh/kg dry solids (Müller, 2000).

Disintegration with ozone
Application of ozone presents a chemical method of sludge disintegration. Due to ozone action, a disruption of microbial cell membranes occurs, accompanied with a release of the intercellular material. Additionally, application of ozone brings on partial oxidation of slowly degradable material to simple readily biodegradable forms. Hence, at the wastewater treatment plant where the C/N ratio is not favorable, disintegrated sludge may serve as an additional source of organic carbon for denitrification.

So far the most popular is disintegration of excess sludge and a part of recycled sludge. The ozone doses varied from 30 gO_3/ kg dry solids to 80 gO_3/ kg dry solids; at these doses floc structure of sludge is no longer noticeable (Ried A. et al., 2002). Energy consumption in this process was 0,6 and 1,7 kWh/kg VSS, respectively.

Mechanical disintegration
At the Technical University of Braunschweig (Müller, 2000 and Lehna 2000) different methods of sludge disintegration were examined. Best results were achieved while using the stirred ball mill or the high- pressure homogenizer (500 x 10^5 Pa). An average energy consumption for these methods was: 0,224 kWh/kg of dry solids and 0,28 kWh/kg of dry solids, for ball mill and homogenizer respectively.

German manufacturers already offer mechanical sludge disintegrators, which use principle of cavitation to rupture microorganism cells. Energy consumption for the method ranges from 0,4 to 0,55 kW/m^3/h.

Process TPAD (Temperature Phased Anaerobic Digestion)
TPAD consist of small thermophilic digester followed by a large mesophilic digester. The first phase achieves 80 to 90% of VSS destrucion and gas production, and the second phase provides additional polishing and deodorizoing (Sieger R. et al., 2001). A tipical TPAD digester design consists of a thermophilic phase with a 5-days detention time, followed by a 10-day mesophilic phase. This design takes advantage of the positive aspects of thermophilic temperatures, while removing undersirable qualities such as the odors and foaming tendencies typical of mesophilic temperatures. According the literature (Sieger R. at al., 2001) the TPAD process can provide advantages also some additional VSS reduction and produces more, higher quality gas.

Pre-Pasteurization
Pre-Pasteurization (or pasteurisation of solids prior to anaerobic digestion) involves heating raw solids to 70^0 C before transferring to a separate holding tank (Sieger R. at al., 2001). The solids in the holding tank are maintained at a minimum of 70^0 C for 30 minutes. When pasteurisation is complete, the solids temperature is decreased to about 40^0 C in a heat exchanger and transferred to the digester. By using a sludge/sludge heat exchanger, over 60% of the thermal energy can be recovered prior to entering the digester.
Pasteurization following mesophilic anaerobic digestion is not acceptable due to pathogen regrowth. Pasteurisation may enhance VSS destruction, but further research is required to valide this claim.

As is readily seen, many alternatives to anaerobic digestion are available, each having its own advantages and disadvantages. As anaerobic digestion revitalizes even more, today's plant and biosolids managers must stay abreast of technology with an eye to enabiling their existing digester to handle considerably more solids, and produce greater quantities of gas at less cost than constructing more digesters (Sieger R. at al., 2001).

Sludge disintegration is carried out mostly to intensify sludge treatment and enhance biogas production; other outcomes such as utilization of intermediate products (VFA and other easily biodegradable organics) becomes only a partial goal of the process. This effect provides a valuable loading of easily biodegradable organics necessary for biological nutrient removal in the biological reactors.

LABORATORY EXPERIMENTS ON ANAEROBIC SLUDGE DIGESTION

Laboratory experiments have been initiated on wastewater sludge disintegration at the Cracow Technical University. The experiments were conducted using the waste sludge from the Gdańsk – Wschód wastewater treatment plant. Before the experiments, the sludge had undergone preliminary and separate hydrolysis at the controlled temperature of 70C.

Materials and methods

Equipment

The experimental instruments included:

- ANR-100 respirometer for anaerobic experiments
- water bath with magnetic mixer
- computer program for automatic data collection

Anaerobic biomass source

The experiments were conducted using waste sludge from the Gdańsk – Wschód wastewater treatment plant. The sludge was additionally inoculated with the digested sludge withdrawn from the plant anaerobic digesters.

Test conditions

Temperature of the preliminary hydrolysis – 70C
Temperature of sample digestion – 35C
Initial pH of the sample – approx. 7.0
It was assumed, that the content of organic solids in analyzed anaerobic sludge samples would be: approx. 9g/L (digested sludge for inoculation) and approx. 12-16 g/L (mixed samples). Due to a high biomass concentration in the samples, the tests were performed as batch tests with mixing.
The process was ceased when stabilization of biogas production was observed. It was assumed that a test time for each sample is 20 days. Sludge hydrolysis was performed at three different periods: 30 min, 24 h, 72 h and 7 days.

The volume of produced biogas was automatically registered, every 2h, using ANR-100 respirometer. The volume of methane gas was determined based on the chromatographic analysis of a biogas content. The following parameters have been used to identify the course of anaerobic processes during the batch tests: COD, solids and organic content in the sludge, pH, ammonia nitrogen and alkalinity.

Analytical methods
One-liter flasks were used as reaction chambers in this study. The flasks were filled with the following medium:
Sample 1 – digested sludge (used as an inoculation of waste sludge samples),
Sample 2 – waste sludge, without preliminary hydrolysis + digested sludge (reference sample),
Sample 3 - waste sludge, after 30 min of preliminary hydrolysis + digested sludge,
Sample 4 - waste sludge, after 24 h of preliminary hydrolysis + digested sludge,
Sample 5 - waste sludge, after 72 h of preliminary hydrolysis + digested sludge,
Sample 6 - waste sludge, after 7 days of preliminary hydrolysis + digested sludge, ,

Plastic tubes connected the samples with the respirometer; the detected values were automatically registered in the computer.

Results of the experiments

Sludge characteristics
Table 1 presents the results of the chemical analysis of both digested and thickened waste sludge. The dry solids content in digested sludge was 28.1 g/L (62.6 % of organic fraction). The sludge concentration was lower then the values obtained during digestion, therefore the values of other parameters such as e.g. sludge alkalinity were also found lower. Waste sludge had also a lower dry solids content than the sludge after a thickening process at the plant. An organic fraction in the sludge was 71.3 %. Lower concentrations of sludge did not have an impact on the course of experiments.

Discussion

Digested sludge
Table 2 presents the calculated volumes of biogas and methane produced per unit of organic mass removed. Removal of 1 kg of organic solids produces 587 L of gas.
During the course of sludge digestion, a fraction of organics in the total sludge mass dropped from 63.9% to 56.9 %. The volume of produced gas, as a function of time can be calculated by the following formula:

$$V = V_{max} (1-e^{-kt})$$

The value of the constant k is 0.19.
Further digestion of sludge allows for removal of an organic fraction from the sludge and production of biogas with a large amount of methane.

Digested sludge + waste sludge
In the sample mixed with waste sludge and not preheated, the lowest drop of an organic fraction was observed (table 3). The lowest removal 29% was observed for sludge without preheating. The gas production rate was shown in Figure 3. The sludge which was not preheated exhibits the highest production rate during the first day of digestion. This sample generated also the largest volume of gas per 1 kg of biomass removed (980 L/kg). The produced biogas showed a low methane content (50%). The amount of methane produced per 1 kg of biomass removed (table 2) is lower then in the samples that had been previously preheated.

As the time of preliminary hydrolysis extended (0.5h, 24h, 72h) the value of organic fraction in sludge decreased from 60 to 58.9 %. In the sample 4 (with 24h hydrolysis) the fraction of organics was higher but the digestion time in this case was only 14 days, and not 21 days as in the other samples with 30 min and 24 h hydrolysis, or 18 days for the sample with 72h hydrolysis.

Table 1. Characteristics of waste sludge and digested sludge

	Units	Digested sludge	Waste sludge
pH		7,51	6,02
Dry solids	[g/L]	28,1	37,3
Dry organic solids	[g/L]	17,6	26,6
Organic fraction	%	62,6	71,3
Alkalinity	mg $CaCO_3$/L	4250	1150
ChZT	gO_2/L	28,420	53,760
Ammonia nitrogen	mgN/L	780,2	61,6

Table 2. Production of biogas per unit of dry organic solids removed

	Digested sludge	Digested + waste sludge	Digested + waste sludge 70 ^oC,30 min	Digested + waste sludge 70 ^oC, 24 h	Digested + waste sludge 70 ^oC, 72 h	Digested + waste sludge 70 ^oC, 7 days
Biogas volume [L]	0,705	2,940	2,965	2,996	2,917	2,685
Biogas volume per 1 kg of dry org. solids remov. [L]	587	980	872	847	788	813
Methane volume per 1 kg of dry org. solids remov. [L]	473	519	680	669	637	663

Table 3.Dry solids and organic dry solids in sludge samples before and after anaerobic digestion process

	Digested sludge		Digested + waste sludge		Digested + waste sludge 70 ^oC,30 min		Digested + waste sludge 70 ^oC, 24 h		Digested + waste sludge 70 ^oC, 72 h		Digested + waste sludge 70 ^oC, 7 days	
	C_i	C_f	C_i	C_f	C_i	C_f	C_i	C_f	C_i	C_f	C_i	Cf
Dry solids [g/L]	14,3	13,7	23,3	20,3	24,2	20,8	23,3	19,8	24,4	20,7	22,9	19,6
Dry org. solids [g/L]	9,0	7,8	15,2	12,2	15,9	12,5	15,3	11,8	15,9	12,2	14,9	11,6
Organic fraction[%]	62,9	56,9	65,2	60,0	65,1	60,0	65,6	59,5	65,1	58,9	65,1	59,1

C_i – initial dry solids content
C_f – final dry solids content

Removal of the organic fraction from the waste sludge increased along with the time of hydrolysis; for a 30 min period, its value was 32% while for 24 h period it reached 36%. For other samples, the removal remained at the level of 36% but the digestion time for these cases was shorter. It is

interesting to notice, that in spite of an increase of dissolved COD (as hydrolysis last longer), the biogas production rate decreased during the early stage of digestion.
The volume of biogas produced per 1 kg of organic biomass removed, after 21 days of anaerobic digestion was 800 L. Preheating of sludge resulted in high amount of methane in the biogas.

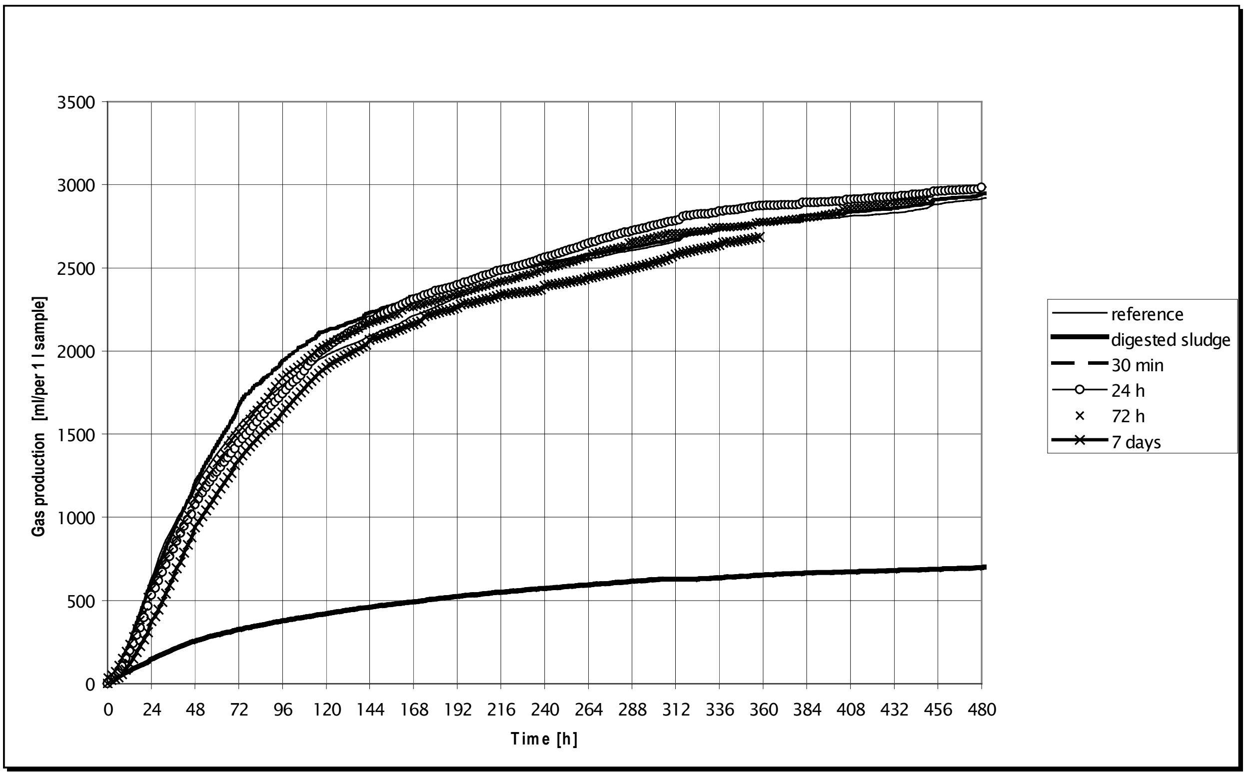

Figure 3. Gas production from test samples of waste and digested sludge

Conclusions

1. Preheating of thickened waste sludge leads to sludge hydrolysis and an increase of dissolved COD in supernatant. The initial dissolved COD in the samples without hydrolysis was 631 mg O_2/L, while for the preheated samples of wasted sludge it increased (depending on the duration of hydrolysis) to from 729 mg O_2/L (pasteurization) to 3980 mg O_2/L (7 days hydrolysis). The increase of dissolved COD, resulted from sludge hydrolysis, did not intensify neither biogas production kinetics during the early stage of digestion nor the overall gas volume.
2. After waste sludge pasteurization or its longer preheating the amount of methane in the overall gas volume increased. The volume of methane in the samples without preheating was 54% of the total sample volume, while in the samples after hydrolysis in 70^0 C and digestion the volume of methane was 80%.
3. Pasteurization of sludge for 30 min at 70^0 C resulted in the increase of an organic fraction removal from waste sludge. The observed removal increased from 28% to 32%. The lengthening of hydrolysis time (24 h, 72 h, 7 d) resulted in an increase of an organic fraction removal up to 36%.
4. The content of dry organic solids in waste sludge was 23 kg/m^3. An increase of dry organic solids removal by 8% caused reduction of a dry organic solids concentration in digested sludge by 1.8 kg/m^3.

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