INFLUENCE OF TEMPERATURE VARIATION ON BIOGAS YIELD FROM INDUSTRIAL WASTES AND ENERGY PLANTS

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Abstract. The influence of temperature on the performance of anaerobic digestion of industrial wastes and energy plants has been investigated. Continuous digestion of industrial wastes and energy plants was carried out for 120 days at different temperature. The variation of temperatures ranges from 52 ºC to 57 ºC while keeping other parameters constant such as the total solid concentration, organic load and pH. The highest biogas yield from industrial wastes and energy plants was found at 52 ºC with average yield of 674.4 $l \cdot kg^{-1} \cdot VS^{-1}$ and energy value of 14.2 $MJ \cdot kg^{-1} \cdot VS^{-1}$. By rising temperature to 57 ºC there was a rapid initial drop in the biogas yield rate averaging yield 512.3 $l \cdot kg^{-1} \cdot VS^{-1}$ and energy value of 10.2 $MJ \cdot kg^{-1} \cdot VS^{-1}$. In addition, the temperature fluctuations influence variations of biogas production significantly.

Keywords: thermophilic process, biogas, anaerobic digestion, industrial wastes, energy plants.

Introduction

Anaerobic digestion is a method for organic waste disposal. At the same time anaerobic fermentation significantly reduces the total mass of wastes, generates solid or liquid fertilizers and produces energy [1; 2]. It can be maintained at psychrophilic (16-25 ºC, e.g. in landfills, swamps or sediments), mesophilic (35-40 ºC, e.g. in the rumen and anaerobic digesters) and thermophilic conditions (52-60 ºC; e.g. in anaerobic digesters or geothermally heated ecosystems).

The optimum digester temperature setting, considering both the potential biogas yield and energy value, is one of the most critical factors for the economically viable digester operation in modern countries. Researches have suggested that the gas production during anaerobic digestion is correlated to temperatures [3-6]. However, different results show that temperature had no effect on the methane yield of beef cattle manure between 30 and 60 ºC [1]. Other researchers suggest that an increase of the temperature results reduction of the biogas yield due to the increased inhibition of free ammonia (NH_3) which increases at elevated temperatures [7].

Stability of an anaerobic digester is often defined as the ratio of the concentration of total organic volatile fatty acids (VFA) to the total alkalinity within a digester. Digesters operating at lower temperatures are considered to be more stable systems [3]. Thermophilic anaerobic processes are more sensitive to temperature fluctuations and require longer time to adapt to new temperature conditions. Disadvantages of thermophilic anaerobic fermentation are the reduced process stability and the requirement for higher energy input for heating. The thermal destruction of pathogenic bacteria at elevated temperatures is considered as an advantage. Thermophilic bacteria tolerate temperature fluctuations of ± 0.5 ºC per hour without significant reduction of methane production. The growth rate of methanogenic bacteria is higher at thermophilic temperatures making the process faster and more efficient [8; 9]. Therefore, the higher organic loading rate (OLR) can be applied for thermophilic digester or it can be operated at shorter hydraulic retention time (HRT) compared to mesophilic conditions. At the same time the thermophilic process results in a larger degree of imbalance and a higher risk for ammonia inhibition. Ammonia toxicity is intensifying with temperature increase [10]. The aim of this paper is to investigate the performance of anaerobic digestion in terms of biogas yield and quality at different temperatures.

Materials and Methods

The experimental system was set up and monitored in the Energy and Biotechnology Engineering Institute located in the Aleksandras Stulginskis University in Lithuania. Seed material (inoculum) was taken from laboratory experiments on wastewater sludge with a starting temperature of 52 ºC. Temperature of mixture of stillage and cocksfoot grass was 49 ºC. This temperature was simulated regarding information from two biogas plants in Lithuania operating on stillage and average temperatures of grass silage found from the experimental farm.

The laboratory anaerobic digester of 20 liters of total volume was operated with an active volume of 19 liters. The design of the anaerobic digester enables to perform experiments in the temperature range from 20 ºC to 65 ºC. The laboratory anaerobic digester system (Fig. 1) consists of: steel vessel 1, process substrate stirrer 10 and gear 2, pH electrode 3, biogas flow meter 4 and gasholder 5, biogas composition analyser 6. The temperature in the digester is measured by temperature sensors 13 and controlled by the heating system 12 automatically as well as mixing of process substrate. The data of temperature and pH of process substrate, biogas yield and composition are registered by programmable logic controller 7 and stored in the computer database.

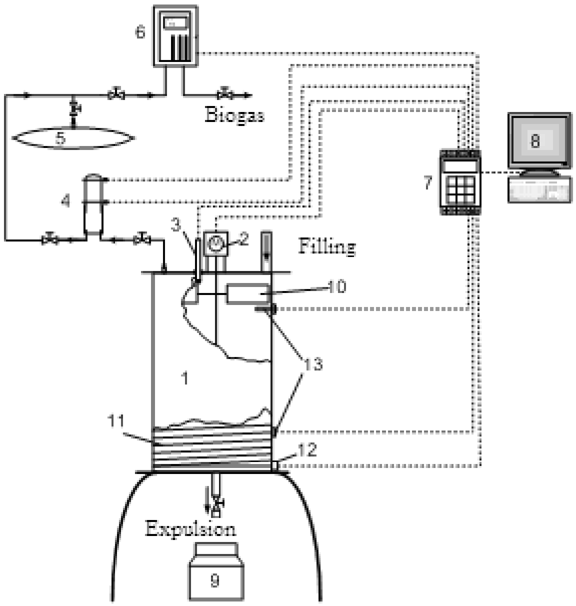

Fig. 1. **Laboratory anaerobic digester**: 1 – digester; 2 – gear of mixer; 3 – pH electrode; 4 – biogas flow meter; 5 – gasholder; 6 – biogas analyzer; 7 – programmable logic controller; 8 – computer; 9 – digested process substrate vessel; 10 – stirrer; 11 – heater; 12 – heating system; 13 – temperature sensors

The produced biogas is collecting at the top of the digester and goes through the biogas flow meter 4 to gasholder 5. Later the collected biogas is analysed by SSM 6000. During the experiments the biogas composition – methane (CH_4) and hydrogen sulphide (H_2S) were measured. The biomass is added through the tube on the top of the digester and the digested process substrate drains to the digested process substrate vessel 9.

The anaerobic digestion process takes place at thermophilic (52-57 ºC) temperature conditions. Digesters were operated at 52 ºC, 53 ºC, 54 ºC, 55 ºC, 56 ºC and 57 ºC. The internal temperature of the process substrate in the digesters has been controlled with an accuracy of ± 0.2 ºC. Keeping of constant temperature during the digestion process is important, as temperature changes or fluctuations can negatively affect the biogas yield. After each temperature change the digester was left at the new temperature for at least 1 week before the next temperature shift. One cycle of the experiments took 18 days. It was considered that a steady-state had been achieved when the biogas yield rate varied by less than 3 % on three consecutive days [5; 6].

The statistical analysis was done using Stat software adapted in the Visual Basic for Application as macro program to run in the Excel.

The reactors were loaded with wheat ethanol stillage and cocksfoot grass silage by ratio 3:1 and using 1.0 $kg \cdot m^{-3} \cdot d^{-1}$ organic load. Wheat ethanol stillage had 7.76 % total solids (TS) and silage of cocksfoot grass – 25.2 % TS (Table 1). Therefore, the mixture had a favorable TS concentration for anaerobic digestion.

The results of biomass anaerobic digestion can be evaluated using the following indicators: intensity of biogas production, biogas yield from biomass B_M, biogas yield from biomass total solids B_{TS}, biogas yield from biomass volatile solids B_{VS}, energetic value of biomass obtained at anaerobic conversion e_{VS}. The biogas production intensity b indicates the duration of biomass biological degradation.

Table 1

Characteristics of wheat ethanol stillage and grass silage

Parameters	Sample		Methods
	Wheat ethanol stillage	Cocksfoot grasses silage	
Total solids (TS), %	7.76	25.2	Dried at 105 ºC
In total solids, %:			
Volatile solids (VS), %	95.28	93.92	Incinerated at 550 ºC
Total nitrogen (N), %	5.43	2.39	Kjeldahl apparatus
Organic carbon (C), %	48.30	46.7	Carbon analyser

The biogas yield from biomass, from biomass total solids and from biomass volatile solids B_M, B_{TS}, B_{VS} is calculated by equations [11]:

$$B_M = \frac{b_{dt}}{m}; B_{TS} = \frac{b_{dt}}{m_{TS}}; B_{VS} = \frac{b_{dt}}{m_{VS}}; \quad (1)$$

where b_{dt} – volume of produced biogas during the time interval dt, l;
m – mass of sample, kg;
m_{TS} – mass of total solids in the sample, kg;
m_{VS} – mass of volatile solids in the sample, kg.

The energetic value of biomass obtained at anaerobic digestion of mass of volatile solids, e_{VS} is determined by equation:

$$e_{VS} = b_{VS} \cdot e_b, \quad (2)$$

where e_b – energetic value of biogas which depends on methane concentration in biogas, $MJ \cdot l^{-1}$,
b_{VS} – biogas yield from one kilogram of mass of volatile solids, $l \cdot kg^{-1} \cdot TS^{-1}$.

The energetic value of biogas is determined by equation:

$$e_b = 0.0353 \cdot \frac{C_M}{100}, \quad (3)$$

where C_M – methane concentration in biogas, %.

Results and discussions

The responses of the anaerobic process performance to changes in six different temperatures were investigated. Biogas production with a single temperature was measured during 3 week digestion period. The highest biogas yield at thermophilic temperature range was achieved at 52 ºC with the yield averaging 674.4 $l \cdot kg^{-1} \cdot VS^{-1}$ (Fig. 2, Table 2). The lowest biogas yield was achieved at 57 ºC with the yield averaging 512.3 $l \cdot kg^{-1} \cdot VS^{-1}$. After changing temperature from 52 ºC to 53 ºC, only minor changes in the operating processes were observed. The biogas yield dropped by 3.2 % and was averaging 653.2 $l \cdot kg^{-1} \cdot VS^{-1}$. However, when the temperature was increased from 53 ºC to 54 ºC the efficiency of the process became lower with a significant drop in the biogas yield 6.3 % and was averaging 612.3 $l \cdot kg^{-1} \cdot VS^{-1}$. Moreover, at each 1 ºC temperature shift from 54 ºC to 57 ºC, there was a rapid initial drop in the biogas yield rate. The biogas yield decreased in average by 6.0 % at every time the temperature was increased by 1 ºC.

Major differences in the production of biogas after changing temperatures occur in the first three-four days of the experiment.

The methane (C_M) and hydrogen sulfide (C_S) concentration in the obtained biogas was dependent on the temperature and was in the range of 55.7-59.6 % and 660-832 ppm respectively (Fig. 3). The biogas composition differed according to digestion temperature, with the methane contents in the biogas of 59.3 %, 58.9 % at 52 ºC and 53 ºC, respectively, but these differences were statistically not significant. At 55 ºC the methane content in the biogas decreases most rapidly, then remains constant at 56-57 ºC. The optimal temperature range 52-53 ºC shows that when by increased digestion temperatures only slightly above optimal temperature the methane concentration was reduced by up to 2-3 %. Maximum hydrogen sulfide concentration 875 ppm was reached when the digester was operating at 55 ºC. Operating the digester at 56 ºC temperatures resulted in accumulating of volatile fatty acids [12] that caused decrease in methane (56.3 %) and hydrogen sulfide concentration (660 ppm).

Table 2

Influence of temperature variation on biogas yield

Parameter	Unit	Experiment number					
		1	2	3	4	5	6
Temperature in anaerobic digester T_B	ºC	52	53	54	55	56	57
Biogas yield B_M	$l \cdot kg^{-1} \cdot M^{-1}$	76 ± 0.5	74 ± 0.3	69 ± 0.5	65 ± 0.4	61 ± 0.6	58 ± 0.4
Biogas yield B_{TS}	$l \cdot kg^{-1} \cdot TS^{-1}$	636 ± 3.5	616 ± 2.6	578 ± 4.6	543 ± 3.2	512 ± 4.6	483 ± 3.1
Biogas yield B_{VS}	$l \cdot kg^{-1} \cdot VS^{-1}$	674 ± 4.1	653 ± 2.7	612 ± 4.9	575 ± 3.4	542 ± 4.9	512 ± 3.2

The effect of VFA in this context is that the steady-state operating pH (pH_{sub} = 7.91 ± 0.03) of the digester operated at 52 ºC was lower than that of the digester operated at 55 ºC or higher (pH_{sub} = 7.99 ± 0.03) while the input material pH is constant during all experiment (pH_{mat} = 4.20 ± 0.03) (Fig. 4.), contributing to the relative instability of the higher temperature digesters. Process substrate pH follows discussion of relatively good reactor performance at temperatures ranging from 52-53 ºC, and relatively poor reactor performance at 57 ºC.

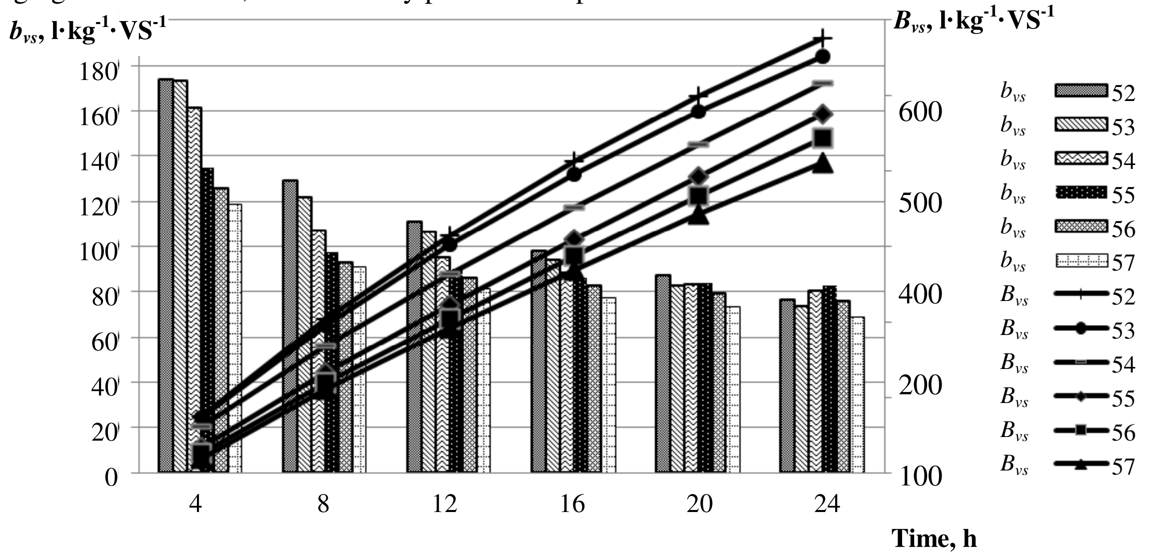

Fig. 2. **Influence of temperature on biogas production rate (b_{vs}) and cumulative biogas yield (B_{vs}) after steady state**

The methane content in the produced biogas is one of the most important indicators. The energy values obtained from the produced biogas from wheat ethanol stillage and cocksfoot grass silage at different temperatures are depicted in Fig. 3.

According to the results, the total energy value was the greatest at 52 ºC, and the temperature increase from 52 to 53 ºC resulted in a decreased energy value from 14.2 $MJ \cdot kg^{-1} \cdot VS^{-1}$ to 13.6 $MJ \cdot kg^{-1} \cdot VS^{-1}$. Operating at 57 ºC, the energy value was the lowest – 10.2 $MJ \cdot kg^{-1} \cdot VS^{-1}$. In contrast, the digestion proceeding at a temperature of 57 ºC showed only 71.7 % of that at 52 ºC.

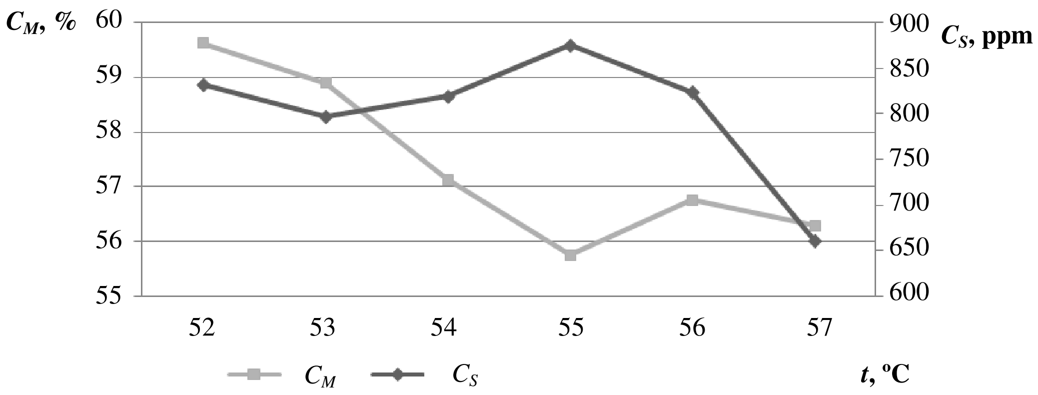

Fig. 3. **Variation of methane and hydrogen sulphide composition within different temperature**

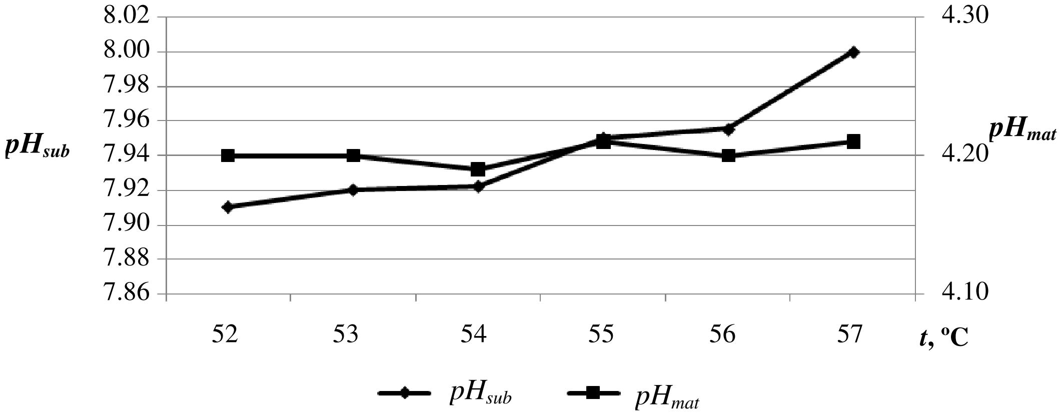

Fig. 4. **Variation of pH of reactor process substrate (pH_{sub}) and input material (pH_{mat}) composition within different temperature**

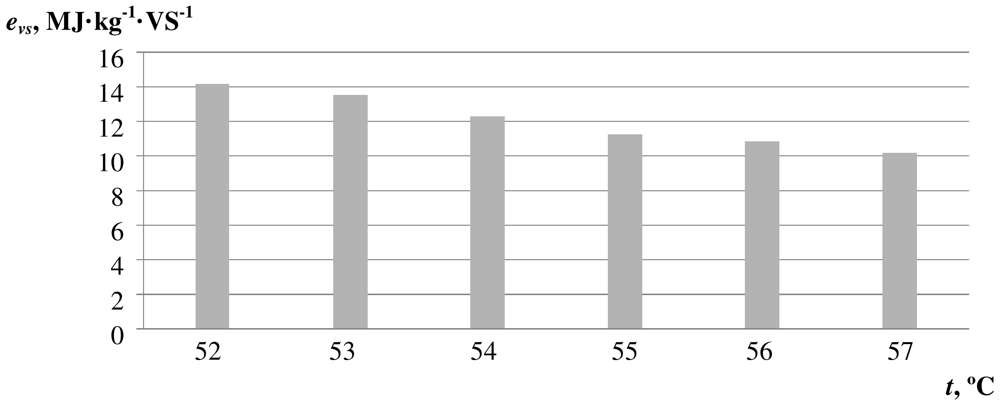

Fig. 5. **Energetic value obtained from one kilogram volatile solids in anaerobic digestion using different temperatures**

Conclusions

1. The optimal temperature range for biogas production from ethanol stillage and cocksfoot grass silage is 52-53 ºC in terms of both, the energetic value and average daily methane production.
2. During all investigation the biogas yields ranged between 512.3-674.4 l·kg^{-1}·VS^{-1}. The highest biogas yield was at 52 ºC conditions with the biogas yield of 674,4 ± 3.9 l·kg^{-1}·VS^{-1}. The lowest biogas yield was at 57 ºC conditions, with the yield of 512,3 ± 3.3 l·kg^{-1}·VS^{-1}.
3. The total energy value was the highest at 52 ºC with 14.2 MJ·kg^{-1}·VS^{-1}. Thermophilic digestion mixture of industrial wastes and energy plants at 52-53 ºC showed the best potential of energy value.

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