

Thermal – expansionary pretreatment of lignocellulosic biomass: an energy feasibility study

Bc. Andrey Kutsay

Supervisor: Ing. Krátký Lukáš, PhD

Abstract

Thermal-expansionary pretreatment is modern technology that can be used in different types of lignocellulosic biomass. Almost all existing bioplants are not using any effective treatment for increasing the yield of the methane production, by some sensitive value. The idea of thermal-expansionary pretreatment lie on molecular level, the sudden rupture of the cell release the potential for further usage. It was measured experimentally that at temperature 185 °C and residence time 40 min the treatment increases biodegradability of wheat straw by around 23 %. Also, it was observed the highest production of methane raises up to 50 %. So, obtained data open us new doors in either implementing the modern technology into existing plants, or building the new generation plants for humanity.

Keywords

Biogas, thermal-expansionary pretreatment, wheat straw, energy balance, biogas yield.

1. Introduction - chapters

It is not the news, all of us know that shortage of nowadays energy sources will appear in coming 50 years. The current research and future predictions say, the crude oil will use up within 40 to 70 years, and natural gas would be exhausted within the 50 years [1]. Also, the global average temperature would be increased by 1.4 to 5.8 °C by year 2100 and will only continue to grow [2]. The reason of the following temperature change is greenhouse effect, the emitted CO₂ is staying in the atmosphere and it somehow absorb the radiation from the Sun.

At this point it is clear, that in the closest future we need to find new solutions of energy demands for human needs. Nevertheless, these solutions should be effective, differ in pollution rates and be covered by national standards. There are several methods of processing substrate for methane production, but, unfortunately, none of them is effective from the biodegradability point of view. This paper would be dedicated only to special pretreatment of a substrate (wheat straw), which will increase biodegradability. Nevertheless, the following pretreatment could be applied for other types of feedstock.

Before speaking about the modern pretreatment technology we should understand the biology. Lignocellulosic biomass is generally composed of cellulose, hemicellulose, lignin and different other organic and inorganic compounds. The long-chain carbohydrates present in insoluble structure such as cellulose, hemicellulose, and starch cannot be simply broken into short-chain, because of consisting inside lignin [3]. The lignin serves as the glue between chains, and that is why some pretreatment should exist in any bio-fuel plant. Without pretreatment the hydrolysis would not be effective, means that the most potential part of a substrate would not be released for further fermentation.

For better understanding on the figure below you could see the production steps of biogas. The carbohydrates, fats and proteins are broken down into short-chain such as, proteins are broken down into amino acids by proteases, fats are broken down into fatty acids and glycerine by lipases [3].

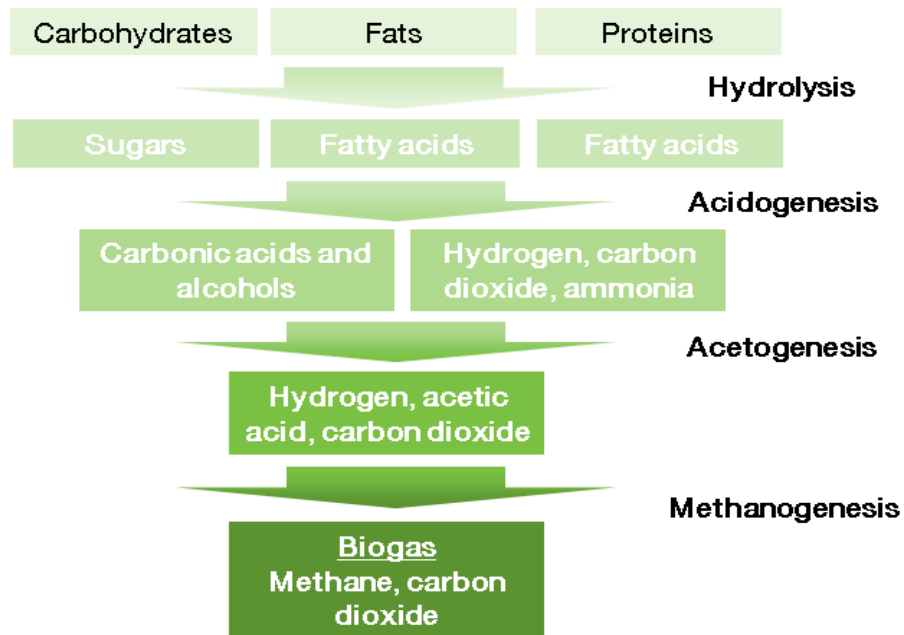


Figure 1. Production steps of biogas.

Usual industrial pretreatment of biomass use chemical dissolution of the lignocellulosic bonds. However, both inhibitory compounds for a microbial system are formed [4], and hydrolysate must be chemically stabilized owing to anaerobic conditions.

In comparison with chemical pretreatment the hydrothermal treatment looks quite less aggressive and easier to control. So that, it is possible to convert around 60% wt. of organic volatile solids from lignocellulosic biomass to a liquid [5] and hemicellulose removal up to 80% wt [6].

The one from hydrothermal pretreatment is steam explosion. During this treatment lignocellulosic biomass is put into a reactor, where high temperature steam up to 240 °C and pressure is applied for a few minutes [7]. When the system reach the residence time, the batch is quickly depressurized. Liquid, which is sucked into the biomass pores, changes its phase to vapour and the associated volumetric change causes a high disruption of the lignocellulosic bonds. The effectiveness of a steam explosion particularly depends on particle size, its composition and humidity, on steam temperature and on residence time [5].

Thermal-expansive pretreatment is advanced technology in processing the lignocellulosic biomass for different types of substrate. The following pretreatment consist of 2 stages: boiling of a mixture (95% wt. of water) under high pressure, and sudden decompression.

2. Feedstock

Wheat straw was chosen as the feedstock for thermal-expansive pretreatment. It is one of the most founded agricultural wastes. So, wheat straw was collected from the fields and has been stored in some storage with in the ambient temperature. The total solid content (TS) is 92% wt. and the volatile solid content (VS) is 86% wt. Also, was defined content and elementary composition of wheat straw [8].

Table 1. Content of wheat straw [8].

Cellulose	[%] wt.	34.1
Hemicellulose	[%] wt.	37.0
Lignin	[%] wt.	22.8

Table 2. Elementary composition of wheat straw [8].

Carbon	[%] wt. TS	39.2
Hydrogen	[%] wt. TS	5.2
Oxygen	[%] wt. TS	41.6

3. Thermal – expansionary pretreatment, experimental procedure

3.1 Lab – scale

Thermal – expansionary pretreatment was used in batch mode [9], see figure 2. Briefly, the hydrolyser is batch double-jacketed pressure vessel, which could be filled maximum by 8 l. Wheat straw is heated by oil (O) in double-jacketed vessel. The expansion vessel (2) is used to keep the expanded substrate. The dump valve (V2) is used to discharge the hydrolysate (expanded substrate). Expansion vessel is equipped with water (W) cooling system. The ball valve (V1) keeps the pressure in hydrolyser, which is gained during heating. At first, the hydrolyser is filled with the mixture of substrate and water (95% wt.). The mixture is heated by oil up to some desired temperature, as the hydrolyser is closed the pressure is increased. The ball valve opens and the mixture is expanded in expansion vessel due to different pressure difference in both vessels. The products of sudden expansion is vapour and hydrolysate.

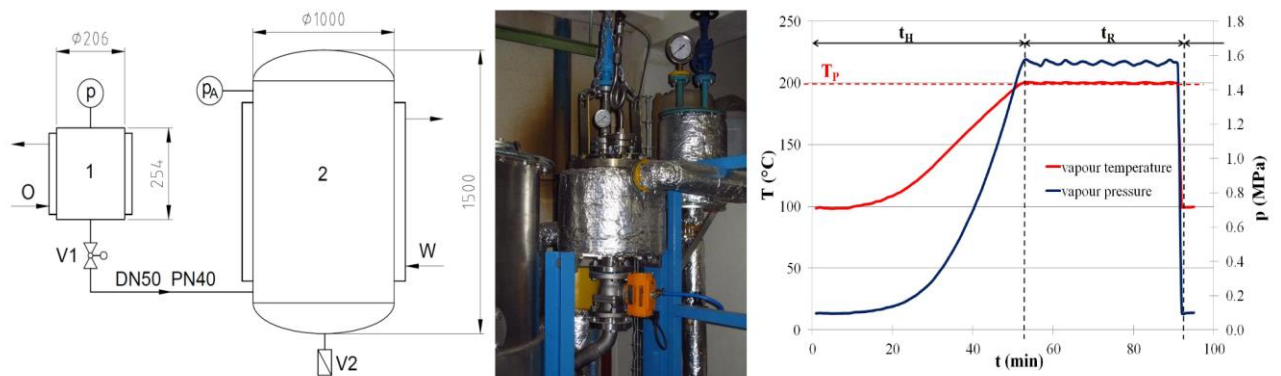


Figure 2. Laboratory unit for the thermal-expansionary treatment. 1-hydrolyser, 2-expansion vessel, V1-ball valve with pneumatic actuator, V2-dump valve, W-water cooling [9].

3.1.1 Results

During experiment, the best degradation of raw material was achieved at 185 °C and 40 min of residence time [8]. On the following table and figures, you could see the results of the experiment, which are very important for further investigations.

Table 3. Table of important data [8].

Sample	Specific production [Nm ³ /t TS]				
	Y_{BG} average	Biogas formation [%] wt. - C_{BG}^m	Y_{CH4} average	CH ₄ formation [%] wt. - C_{CH4}^m	Increase in CH ₄ production
untreated straw	509 ± 58	60	243 ± 49	28	-
185 °C /40 min	532 ± 52	64	299 ± 29	33	23 %
Milled + 185 °C /40 min	633 ± 52	76	362 ± 43	34	49 %

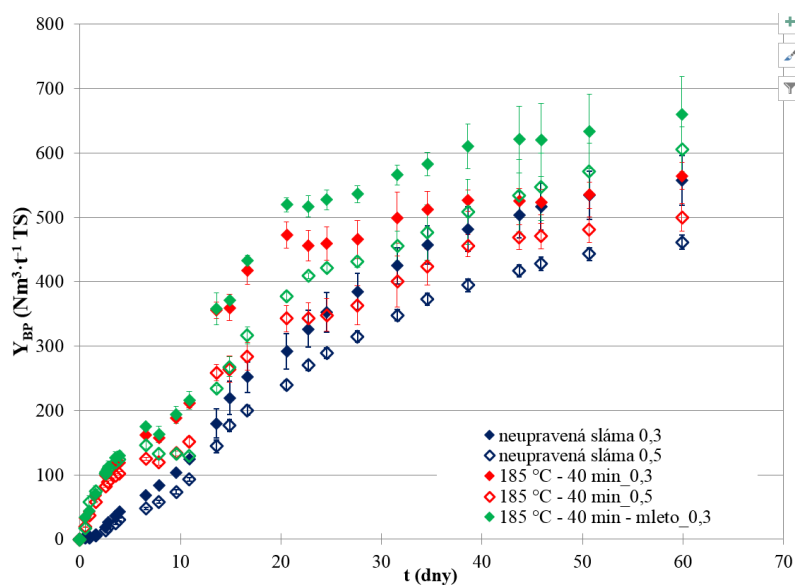


Figure 3. Biogas yield [8].

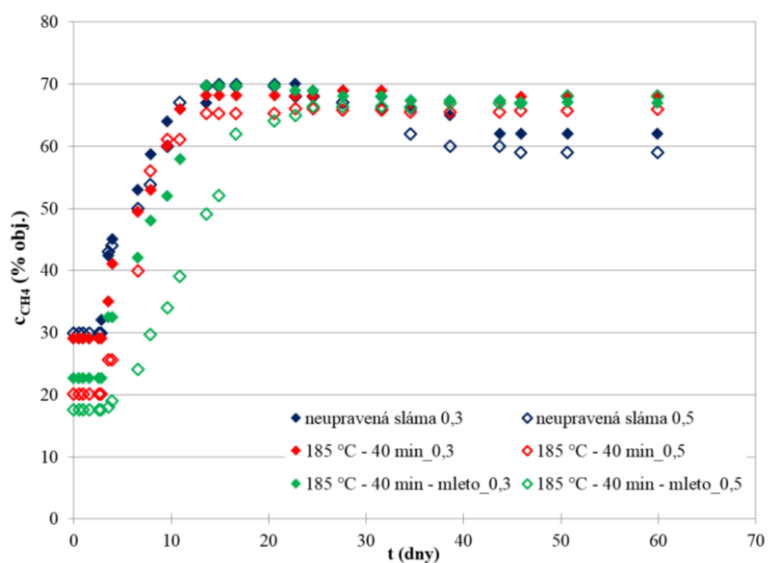


Figure 4. Volume concentration of methane (CH₄) in biogas [8].

The table describe us the average values of biogas and methane yield. It could be seen, that when the substrate is milled and treated under 185 °C and residence time is 40 minutes, it has the best yield data.

Now we can use the obtained data in practise of biogas plant model. Let us calculate the amount of untreated substrate for production of electric power 500 kW in cogeneration unit. The following formula obtained,

$$\dot{m}_{TS} = \frac{\dot{Q}}{\eta_E \times q_{CH_4} \times Y_{CH_4}} \quad (1)$$

$$\dot{m}_{TS} = \frac{500}{0.38 \times 9.94 \times 243}$$

$$\dot{m}_{TS} = 0.545 t_{TS} / h = 0.152 kg_{TS} / s$$

As the feasibility prove of previous number the following table was found. It describes the amount of added energy to produce the corresponding electricity within the cogeneration unit [12].

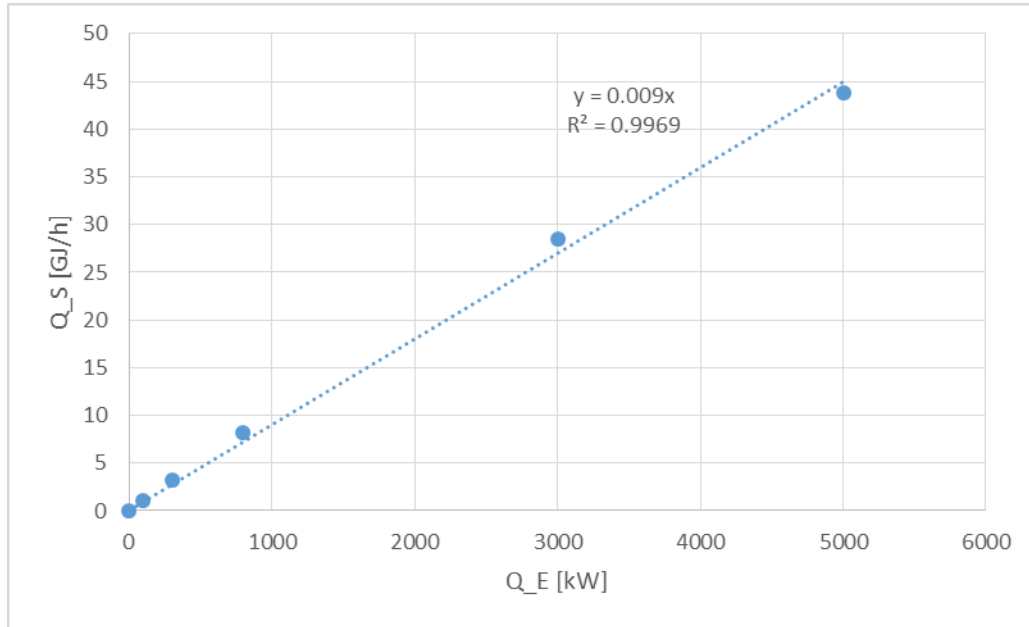


Figure 5. Energy vs. Power linear curve [12].

So, if we want to estimate the supplied power of cogeneration unit, we can use linear equation, and for Q_E value we will use 500 kW,

$$\dot{Q}_S = 0.009 \times \dot{Q}_E \quad (2)$$

$$\dot{Q}_S = 0.009 \times 500 = 4.5 GJ / h$$

We know that low heating value (LHV) of methane is 50 MJ/kg, and the methane formation within the biogas formation (60%) is 28 % (mass balance estimation). Now we can check the results,

$$\dot{m}_{CH_4} = (\dot{m}_{TS} \times C_{BG}^m) \times C_{CH_4}^m \quad (3)$$

$$\dot{m}_{CH_4} = (0.152 \times 0.6) \times 0.282 = 0.026 kg / s = 92.6 kg / h$$

Therefore, the supplied energy will look like,

$$\dot{Q}_s = \dot{m}_{CH_4} \times LHV \quad (4)$$

$$\dot{Q}_s = 92.6 \times 50 = 4629 MJ / h = 4.6 GJ / h \approx 4.5 GJ / h$$

3.2 Plant – scale

3.2.1 Flowsheet

The flowsheet of thermal – expansionary pretreatment technology was constructed. The following flow sheet is adapted, for 5 % wt. of substrate and 95 % wt. of water, for treated substrate.

The stream 1 (substrate) is mixed with stream 9 (heated water) and sent to Milling machine (C-101) by screw conveyor (J-100). The mixing of heated water and substrate is done for intensification of the milling in milling machine [10]. The stream 2 is sent to vessel (M-104) and mixed with stream 8 (heated water). The stream 8 heated by heat exchanger, which is used for cooling of treated substrate (not depicted). The mass flow rate of these two streams (2, 8) is essential, so that the mass fraction of water within two streams is equal to 95 %. After the mixing, the stream 3 sent to extruder (R-105). Extruder playing the crucial part in this technology. The inlet mixture (stream 3) is pressurized from 1 to 8 bar, at the same time it is heated by compressed steam (stream 11), which was the outlet from expansion vessel (F-107). The stream 4 processed after in jacketed vessel with screw conveyor (M-106). This jacketed vessel is used for heating of pressurized mixture up to 185 °C, as it was discussed in “Lab – scale” chapter. Jacketed vessel feed by exhaust gases, which were created within the combustion of biogas in cogeneration unit. The surplus of exhaust gases energy that is left after heating of vessel M – 106, is used for heating of stream 7. Finally, after all, the stream 5 rapidly expanded inside the expansion vessel, where the soaked water inside substrate immediately evaporated, due to difference of pressure. The fibers of substrate disrupted to the powder level. The treated substrate is now ready for fermentation process.

For more details, please look to Figure 6.

The treated substrate has higher potential than untreated one (chapter 3.1.1). Using the formula 1, we can estimate the electricity production with same untreated substrate amount for 500 kW,

$$\dot{Q} = \dot{m}_{TS} \times \eta_E \times q_{CH_4} \times Y_{CH_4} \quad (5)$$

$$\dot{Q} = (0.152 \times 3600 / 1000) \times 0.38 \times 9.94 \times 362 \cong 750 kW$$

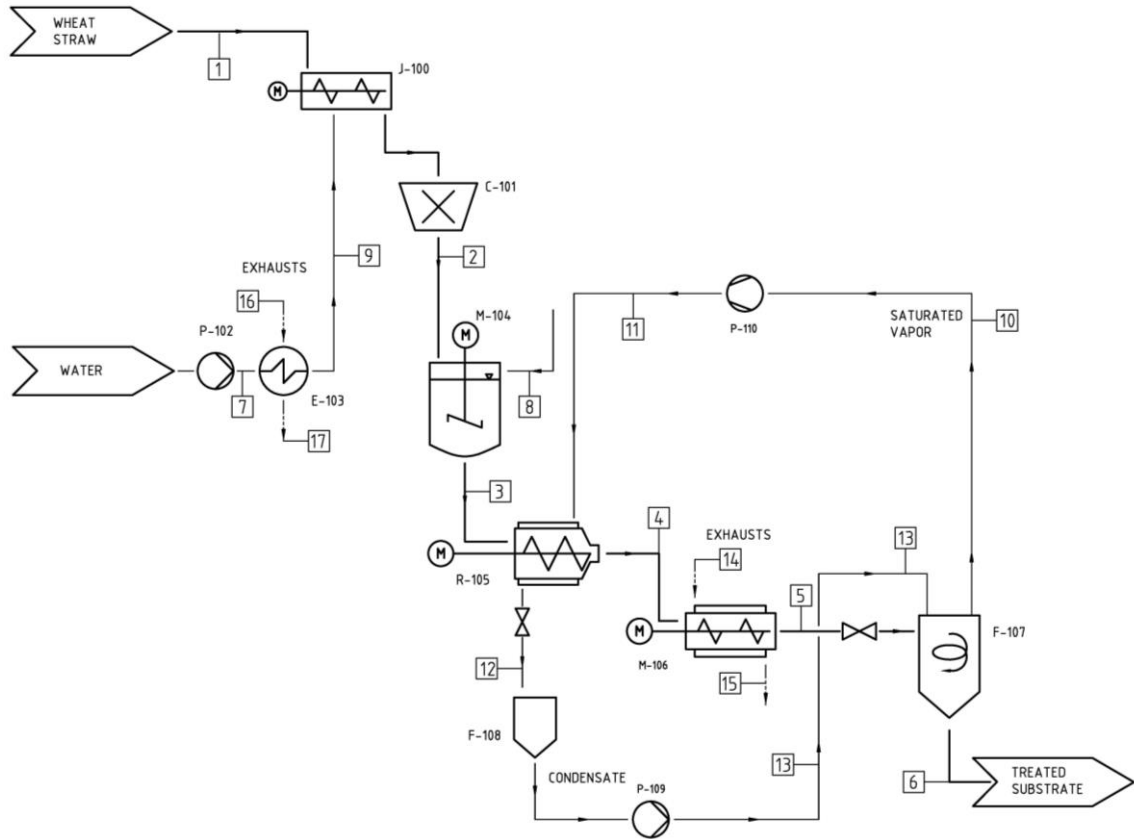


Figure 6. Flowsheet of Thermal – expansionary pretreatment technology.

3.2.2 Energy Balance and Regeneration

The energy balance is calculated for 3 apparatuses: extruder (R-105), jacketed vessel with screw conveyor (M-106), and heat exchanger (E-103). For all 3 apparatuses the energy was regenerated.

- *Extruder (R-105)*

The energy balance based on heat transfer from hot stream (saturated vapor at 8 bar) to cold stream (mixture). The mixture is considered to be water, as the content of water is 95% wt.

$$Q = m_{11} \times (h_{steam} - h_{water}) = m_3 \times C_{p_water} \times (T_4 - T_3) \quad (6)$$

$$0.41 \times (2767.9 \times 10^3 - 719.2 \times 10^3) = 3.04 \times 4200 \times (T_4 - 92)$$

$$T_4 = 157^\circ C$$

- *Jacketed vessel (M-106)*

The energy balance based on heat transfer from hot stream (exhaust gas) to cold stream (mixture). The exhaust stream was taken from combustion of biofuel in cogeneration unit.

$$Q = m_{14} \times C_{p_exhaust_gas} \times (T_{14} - T_{15}) = m_4 \times C_{p_water} \times (T_5 - T_4) \quad (7)$$

$$1 \times 1100 \times (530 - T_{15}) = 3.04 \times 4200 \times (185 - 157)$$

$$T_{15} = 207^\circ C$$

- *Heat exchanger (E-103)*

The energy balance based on heat transfer from hot stream (exhaust gas) to cold stream (water). The residuals of energy from hot stream in jacketed vessel (M-106) is to be used again.

$$Q = m_{16} \times C_{p_exhaust_gas} \times (T_{16} - T_{17}) = m_7 \times C_{p_water} \times (T_9 - T_7) \quad (8)$$

$$1 \times 1100 \times (207 - T_{17}) = 0.101 \times 4200 \times (92 - 15)$$

$$T_{17} = 178^\circ C$$

- *Stream 8 (prove of feasibility)*

The feasibility of stream 8 heating described. The hot stream (expanded mixture) heats the cold stream (water).

$$Q = m_6 \times C_{p_water} \times (T_6 - T_6') = m_2 \times C_{p_water} \times (T_8' - T_8) \quad (9)$$

$$3.04 \times 4200 \times (100 - 75) = 2,8 \times 4200 \times (T_8' - 65)$$

$$T_8' = 92^\circ C$$

3.2.3 Economical Calculation

The economical analysis calculated for biogas plant with thermal-expansionary pretreatment, for electricity production 750 kW.

3.2.3.1 Capital Cost

The capital cost of a plant is estimated using factorial method, which has error $\pm 30\%$. The factorial method of cost estimation based on purchased equipment costs and therefore requires good estimates for equipment costs. In this work the preliminary estimates was made with help of correlations and formula [11].

$$C_e = a + b \times S^n \quad (9)$$

On the table below, you could see the price of each equipment.

Table 4. Capital cost estimation.

Number	Name	Key parameter	capital cost [\\$]
B-203	Burner	duty, MW	9268
C-101	Milling machine	kg/h	14700
E-103	Heat exchanger	area, m ²	1950
E-108	Heat exchanger	area, m ²	18100
E-111	Heat exchanger	area, m ²	11300
E-120	Heat exchanger	area, m ²	11300
F-107	Expansion vessel	capacity, m ³	9208
F-200	Conical vessel	capacity, m ³	9208
F-117	Conical vessel	capacity, m ³	39093
F-118	Vessel	capacity, m ³	9208
F-301	Vessel	capacity, m ³	9208
F-400	Vessel	capacity, m ³	9208
F-402	Distribution tank	capacity, m ³	9208
G-500	Ventilator	m ³ /h	7195

G-600	Ventilator	m ³ /h	6789
G-601	Ventilator	m ³ /h	6789
G-701	Ventilator	m ³ /h	6071
H-400	Biofilter	capacity,m ³	110153
H-115	Centrifuge	power, kW	80694
H-501	Biogas Purification	ref.	30894
J-100	Screw conveyer	ref.	4634
J-109	Screw conveyer	ref.	4634
M-104	Agitated vessel	volume,m ³	18784
M-106	Jacketed vessel with scr. con	volume,m ³	467558
M-110	Vessel	volume,m ³	19816
M-113	Fermentation Vessel	volume,m ³	1440000
P-102	Liquid pump	flow Liters/s	3307
P-109	Screw pump	ref.	4119
P-112	Screw pump	ref.	4119
P-114	Screw pump	ref.	4119
P-110	Compressor	power, kW	36753
P-119	Liquid pump	flow Liters/s	3469
P-201	Liquid pump	flow Liters/s	3316
P-300	Liquid pump	flow Liters/s	3410
P-401	Liquid pump	flow Liters/s	3796
R-105	Extruder	volume,m ³	461337
Q-502	Cogeneration unit	kW	900000
Capital Cost			3.79 mln. \$

Nevertheless, the construction, project costs and other expenses should be counted as well. Rough estimation of total investment cost is plus 20% to capital cost, which is 4.5 mln. \$.

3.2.3.2 Payback time

The payback time was calculated for 30 years of plant lifetime and during production we have three different profits: electricity, substrate residuals, and heat for heating water. Also, we assume the 5 % discount rate, in reality it is not more than 3 %. The bank credit was taken to cover 100% of capital cost. The figures below describe the results of calculation for biogas plant with pretreatment (intensified) and without (non-intensified).

As the production goes, the profit slowly covers the bank credit every year. The analysis is saying that after approximately 12 years for intensified version, and 13.5 years for non-intensified it is going to cover all expenses of bank credit and the plant will start to earn own money. The payback time of both biogas plants will look like,

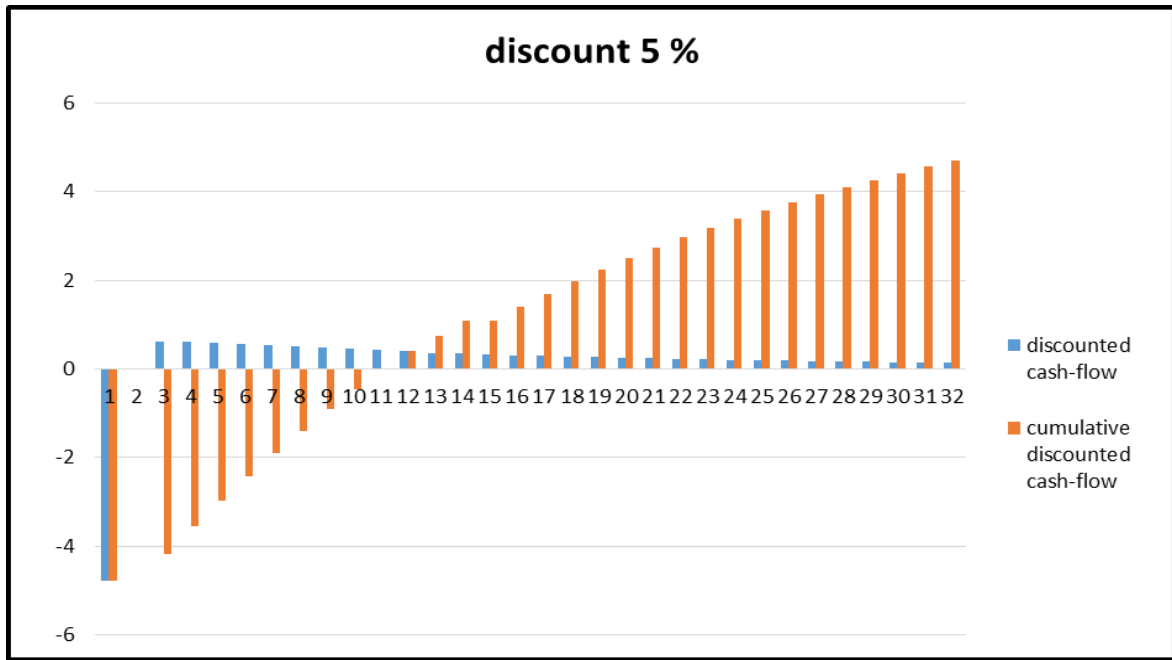


Figure 7. Payback period (5% discount), intensified technology.

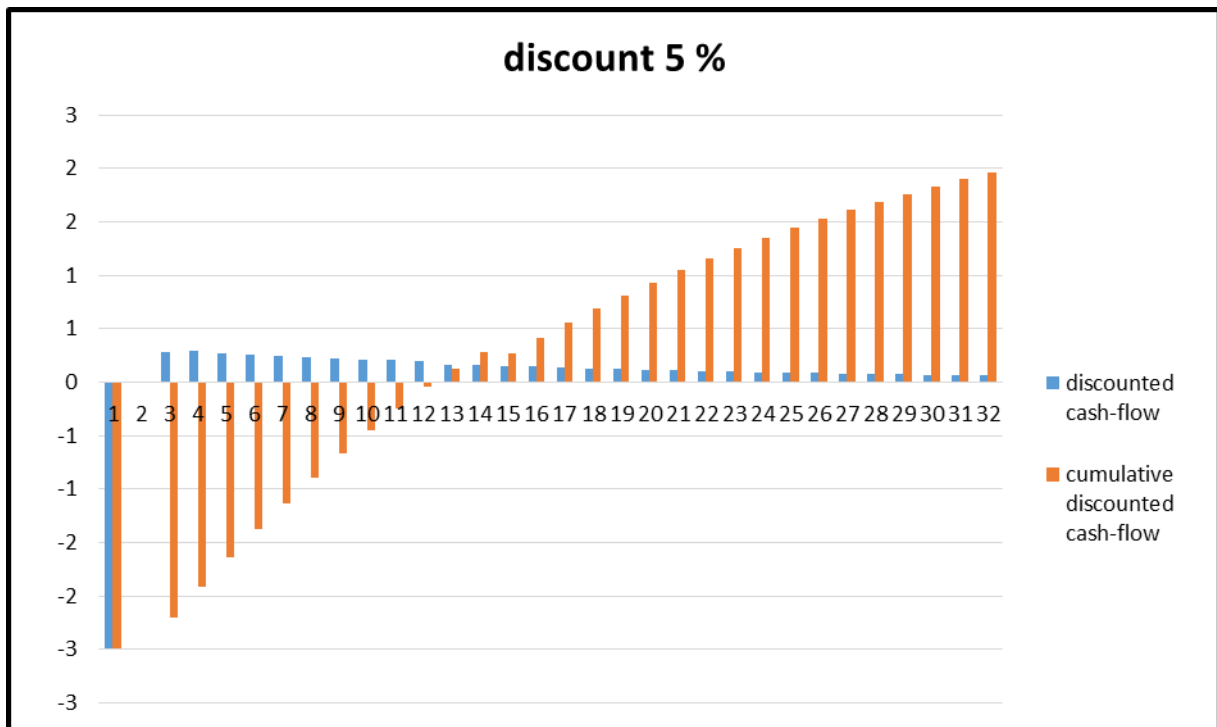


Figure 8. Payback period (5% discount), non-intensified technology.

4. Conclusion.

The main idea of thermal-expansory pretreatment is to improve the yield of methane production. As was shown, with implementing of this technology the methane yield increase by 50% and this number is quite sensitive for production. Nevertheless, the technology seems to be promising in processing of other substrates for various biofuel types.

From economical point of view, constructing new biogas plant with new pretreatment technology, the total investment cost rises from 2.5 mln \$ to 4.5 mln \$, which makes it expensive. For all that, the ability to produce more electricity and selling the heat (by preheating water) covers all expenses, and payback time shorten from 13.5 years to 12 years in comparing to regular biogas plant.

Thermal-expansionary pretreatment is brand new technology for processing of different substrates. Investigations just prove that it is worth to pay attention to it more.

Symbols

l	liters	(l)
LHV	low heating value(heat of combustion)	MJ/kg
\dot{m}_i	mass flow rate of i component	(kg/s)
\dot{Q}_S	supplied energy	(GJ/h)
\dot{Q}_E	electric power	(kW)
\dot{Q}	power	(kW)
η_E	efficiency for electricity production in cogeneration unit	(-)
q_{CH_4}	combustion heat	(kWh/Nm ³)
Y_{CH_4}	methane yield	(Nm ³ /t TS)
y	supplied energy	(GJ/h)
x	electric power	(kW)
C_i^m	concentration of i component	(-)
h_i	enthalpy of i component	(kJ/kg)
C_p	specific heat capacity	(kJ/(kg.K))
C_e	capital cost	(\$)
a,b,n	correlation factors	(-)
S	key parameter	(-)
t	time	(min)
T	temperature	(°C)
p	pressure	(MPa)

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Figure 1. Production steps of biogas.

Figure 2. Laboratory unit for the thermal-expansionary treatment. 1-hydrolyser, 2-expansion vessel, V1-ball valve with pneumatic actuator, V2-dump valve, W-water cooling [9].

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Figure 4. Volume concentration of methane (CH₄) in biogas [8].

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Figure 7. Payback period (5% discount), intensified technology.

Figure 8. Payback period (5% discount), non-intensified technology.

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Symbols	
	Electric Power [kW]
	Air
	Biogas
	Exhaust
	Substrate, Suspension
	Water, fugat

Flow types	
----	Air
-----	Biogas
- - - - -	Exhaust
—	Substrate, Suspension
—	Water, fugat

