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DETERMINING THE THERMAL ENERGY REQUIRED TO HEAT A BIOGAS PLANT FERMENTER

DOLOČITEV OPTIMALNE KOLIČINE TOPLOTNE ENERGIJE ZA OGREVANJE FERMENTORJA V BIOPLINARNI

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The paper presents a procedure for determining the optimal amount of thermal energy for the profitable operation of a biogas plant. The temperature at which anaerobic fermentation takes place shortens the time of fermentation and biogas production, but also the provision of higher temperatures requires a certain amount of thermal energy, whose consumption reduces the energy effects of the biogas production system. In this paper the results of the average outdoor temperature and the temperature of inlet mass in fermenter are shown by months, the thermal energy is calculated so as the heat losses of primary and secondary fermenter, and the total required thermal energy to heat the fermenter by months is determined. The required thermal energy for heating the fermenter is presented in percentages, on average 16 % in relation to the total produced thermal energy. Careful analysis determined that the temperature for most profitable anaerobic fermentation process (mesophilic temperature is 40.5 °C), so that the fermentation rate would be optimal with the use of minimum amount of thermal energy to heat the fermenter.

Keywords: fermenter, biogas, thermal energy, heating

V pričujočem članku avtorji predstavljajo postopek določevanja optimalne količine toplotne energije za rentabilno obratovanje bioplinarne. Višja temperatura pri kateri poteka anaerobni proces fermentacije skrajša čas fermentacije med proizvodnjo bioplina, toda višje temperature zahtevajo povečanje količine toplotne energije, kar zmanjša energijsko učinkovitost bioplinarne. V tem članku avtorji predstavljajo rezultate mesečne povprečne zunanje temperature in temperature vstopne mase v fermentor. Izračunali so toplotno energijo, kot tudi toplotne izgube v primarnem in sekundarnem fermentorju in prav tako celotno zahtevano toplotno energijo fermentorja po posameznih mesecih. Zahtevano toplotno energijo za ogrevanje fermentorja so predstavili procentualno. Ta predstavlja 16 % celotne proizvedene toplotne energije. S skrbno analizo so določili, da je najbolj optimalna temperatura za anaerobni proces fermentacije 40,5 °C. Na ta način je hitrost fermentacije optimalna pri uporabi minimalne količine toplotne energije za ogrevanje fermentorja.

Ključne besede: fermentor, bioplin, toplotna energija, ogrevanje

1 INTRODUCTION

Biogas is a renewable source of energy that is convenient for the production of the electricity and thermal energy.[1,2] It consists of methane and carbon dioxide, a small amount of hydrogen, hydrogen-sulfide, ammonium hydroxide and other gases in trace amounts, and it is not harmful for the environment.[3,4] Biogas is made through a biological process of fermentation, without the presence of oxygen, by which, from the organic mass a mixture of gases, so-called the biogas, is formed. This, in the nature very wide-spread process, takes place in swamps, at the bottom of the sea, in pits for liquid stable dung, as well as in the paunch of cud-chewers.[5–7] Through this, the organic mass, with the help of the range of microorganisms, is almost totally converted into the biogas. In addition, a certain amount of the thermal energy and electricity, as well as new biomass are made.[8–11]

The mixture of gases that is formed mainly consists of methane (50–75 %) and carbon dioxide (25–50 %). Besides, there are small amounts of hydrogen, hydrogen-sulfide, ammonium hydroxide and other gases in trace amounts. The characteristics and content of the biogas depend on the type of the substratum, the method of production, the kind of the device, the temperature under which the process takes place, the duration of the hydraulic persistence, the volume of the digester and other factors. The energy value of the biogas is chemically bound in methane. The approximate thermal value of the biogas is around 6.5 MJ/m^3.[12–14]

2 EXPERIMENTAL PART

The fermenter is the heart of the biogas device and in it the process of the anaerobic fermentation takes place. The fermenter consists of two parts, i.e., the primary and secondary parts.

The primary fermenter is the container, which is made of concrete, and in the shape of a ring, which is projected as an object of the monolithic armored concrete. On its roof there are two controlling windows, so the operator can visually test the state inside of the pri-

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mary fermenter and the process of the anaerobic fermentation.[15–18]

For the appropriate and successful process of the fermentation, it is also necessary to enable the mixing of the matter that is inside the fermenter. The mixing will be accomplished with two pushing mixers and one mixer for dragging. The operation of all three mixers is installed on the roof of the fermenter and the paddles and axle are inside the object.

Apart from the constant mixing, conditions of an appropriate constant temperature should be fulfilled. The constant temperature is necessary for the mesophilic process of creating the biogas by bacteria. The constant temperature inside of the fermenter is kept by the installed system of heating.[19–21]

The system of heating of the fermenter consists of horizontal plastic tubes from the networking polyethylene, which leads along the external round wall of the fermenter, about sixteen lines of tubes. The warm water for the heating of the fermenter is used from the exchanging operator of the heating, which is installed inside the CHP device. The temperature of the water for the heating is about 40 °C and the approximate maximum capacity of the heating of the fermenter of this system is about 140 kW.

The secondary fermenter is placed inside the primary fermenter in the shape of a ring and is also made of the monolithic armored concrete. On its roof there are also two controlling windows, so the operator can visually test the state inside the secondary fermenter. If it is necessary to perform certain tasks such as maintaining the secondary fermenter, biogas will be pulled out only from the primary fermenter. The mixing inside of the secondary fermenter is made with two static mixers in the shape of a paddle, whose operators are also installed on the roof of the secondary digester.

On the concrete roof between the primary and the secondary fermenter, the direct gas connection that is led from the tube of stainless steel, is installed, with the dimension DN 200 (ϕ 200 mm). The connection has a valve and it will make it possible for the biogas to flow from the primary into the secondary fermenter.

The temperature on which the process is made influences the intensity of the anaerobic boiling to a great degree, so there are the following types of the process of boiling:

1. The lower temperature process of the anaerobic boiling that takes place at the temperature of 10–20 °C, and the time of the duration of the decomposition, of approximately 90 % of the organic matter is about 90 d.
2. The medium temperature process of the anaerobic boiling that takes place at the temperature of 30–40 °C, and the time of the duration of the decomposition, of approximately 90 % of the organic matter is about 30 d.
3. The higher temperature process of the anaerobic boiling that takes place at the temperature of 50–60 °C, and the time of the duration of the decomposition, of approximately 90% of the organic matter is about 10 d.

It is clear that higher temperatures under which the anaerobic boiling takes place shorten the time of the fermentation and the production of the biogas, but, at the same time, establishing the higher temperatures requires a certain amount of thermal energy, whose consumption reduces the energetic effects of the system for the production of the biogas.[22–25]

3 RESULTS

In this part of the research the results of the internal consumption of the thermal energy of the device that is necessary for the initial heating of the biomass, which is inserted into the fermenter, are presented.

In **Table 1** is the amount of raw material in the fermenters.

The **Table 2** are the average outside temperatures and the temperatures of the entry mass according to months.

In **Table 3** is the information about the fermenter.

Table 1: Presentation of the amount of the entry raw material into the fermenters

Amount of the entry raw material into the fermenters					
Primary fermenter	18 613 50 993	t/year kg/d	Secondary fermenter	0 0	t/year kg/d

Table 2: Average outside temperatures and the temperatures of the entry mass into the fermenters according to months

month	average outside temperatures (°C)	average temperatures of the mass entry (°C)
Jan.	–4.6	5.0
Feb.	–2.0	6.0
Mar.	2.4	8.0
Apr.	7.7	10.0
May	10.9	12.0
Jun.	16.2	15.0
Jul.	19.7	17.0
Aug.	16.1	17.0
Sep.	10.7	14.0
Oct.	5.8	12.0
Nov.	3.9	8.0
Dec.	–5.1	6.0
	Temperature min. –20.0 °C	Mesophilic 40.5 °C

Table 3: Information about the fermenter

The diameter of the internal ring	24.00 m	The thickness of the internal ring	0.25 m
The diameter of the external ring	35.00 m	The thickness of the external ring	0.28 m
Total height	6.0 m	Pure height	5.5 m

The thickness of the board	0.25 m	The thickness of the upper board	0.25 m
Coefficients			
Specific thermal capacity	1.16 W·h/(kg·K)	The specific thermal conductivity of the substratum	80 W/(m^2·K)
The specific thermal conductivity of insulation	0.41 W/(m^2·K)	Temperature system	20 °C

The necessary amount of the thermal energy for heating of the substratum Q_{ps} is calculated as:

$$Q_{ps} = m_s \cdot c_{ps} \cdot \Delta T \tag{1}$$

where:

m_s – the flow of the mass of the substratum

c_{ps} – the specific thermal conductivity of the substratum

ΔT (°C) – the difference between the temperature of the substrate in the primary fermenter and the entry raw material

Note: The balance is changed with the seasons and the months. The medium monthly temperature is taken.

Table 4 shows the thermal energy that is needed to warm up the primary fermenter.

Table 4: Thermal energy that is needed to warm up the primary fermenter

month	Days (d)	entry-temperature (°C)	fermenter temperature (°C)	temperature difference (°C)	necessary thermal energy (kW)	necessary thermal energy per month (kW·h)
Jan.	31	5.0	40.5	35.5	87.5	65.097
Feb.	28	6.0	40.5	34.5	85.0	57.141
Mar.	31	8.0	40.5	32.5	80.1	59.596
Apr.	30	10.0	40.5	30.5	75.2	54.124
May	31	12.0	40.5	28.5	70.2	52.261
Jun.	30	15.0	40.5	25.5	62.8	45.251
Jul.	31	17.0	40.5	23.5	57.9	43.092
Aug.	31	17.0	40.5	23.5	57.9	43.092
Sep.	30	14.0	40.5	26.5	65.3	47.026
Oct.	31	12.0	40.5	28.5	70.2	52.261
Nov.	30	8.0	40.5	32.5	80.1	57.673
Dec.	31	6.0	40.5	34.5	85.0	63.263
Sum						639.878
Average					73.1	53.323
Maximum					87.5	65.097
Minimum					57.9	43.092

The determination of the loss of the thermal energy through the floor of the fermenter is calculated according to:

$$Q_{pp} = K_p \cdot A_p \cdot \Delta T \tag{2}$$

where:

K_p = 0.41 W/(m^2·K) (the coefficient of the passing through of the thermal energy of the floor)

A_p = 450 m^2 (the surface of the floor of the primary fermenter (the diameter of the primary fermenter D_{pf} = 24.0 m))

A_p = 433 m^2 (the surface of the floor of the secondary fermenter (the diameter of the secondary fermenter D_{sf} = 20.8 m))

ΔT (°C) – the difference of the temperatures in the fermenter and in the feedstock

Note: The temperature difference is changed with the seasons and the months. The medium monthly temperature is taken.

Table 5 shows the losses of the thermal energy to the ground of the primary and secondary fermenters.

Table 5: Losses of the thermal energy to the ground of the primary and secondary fermenter

month	days (d)	average ground temperature (°C)	fermenter temperatures (°C)	temperature difference (°C)	primary fermenter		secondary fermenter	
					necessary thermal energy (kW)	necessary thermal energy per month (kW·h)	necessary thermal energy (kW)	necessary thermal energy per month (kW·h)
Jan.	31	5.0	40.5	35.5	6.6	4.882	6.3	4.697
Feb.	28	6.0	40.5	34.5	6.4	4.470	6.1	4.123
Mar.	31	8.0	40.5	32.5	6.0	4.285	5.8	4.300
Apr.	30	10.0	40.5	30.5	5.6	4.059	5.4	3.905
May	31	12.0	40.5	28.5	5.3	3.919	5.1	3.771
Jun.	30	15.0	40.5	25.5	4.7	3.394	4.5	3.265
Jul.	31	17.0	40.5	23.5	4.3	3.232	4.2	3.109
Aug.	31	17.0	40.5	23.5	4.3	3.232	4.2	3.109
Sep.	30	14.0	40.5	26.5	4.9	3.527	4.7	3.393
Oct.	31	12.0	40.5	28.5	5.3	3.919	5.1	3.771
Nov.	30	8.0	40.5	32.5	6.0	4.325	5.8	4.161
Dec.	31	6.0	40.5	34.5	6.4	4.745	6.1	4.565
Sum						47.989		46.169
Average					5.5	3.999	5.3	3.847
Maximum					6.6	4.882	6.3	4.697
Minimum					4.3	3.232	4.2	3.109
Min. temp. (°C)		0	40.5	40.5	7.5		7.2	

The determination of the losses of the thermal energy through the roofof the the fermenter:

$$Q_{pk} = K_k \cdot A_k \cdot \Delta T \tag{3}$$

where:

K_k = 0.41 W/(m^2·K) (the coefficient of the passing through the thermal energy for the roof)

A_k = 450 m^2 (the surface of the roof of the primary fermenter (the diameter of the fermenter D_{pf} = 24.0 m))

A_k = 433 m^2 (the surface of the roof of the secondary fermenter (diameter of the fermenter D_{sf} = 20.8 m))

ΔT (°C) – the difference of the temperatures of the fermenter and of the surroundings

Note: The temperature difference is changed with the seasons and the months. The medium monthly temperature is taken.

Table 6 shows the losses of the thermal energy through the roof of the primary and the secondary fermenters.

Table 6: Losses of the thermal energy through the roof of the primary and the secondary fermenters

month	days (d)	average outside temperature (°C)	fermenter temperatures (°C)	temperature difference (°C)	primary fermenter		secondary fermenter	
					necessary thermal energy (kW)	necessary thermal energy per month (kW·h)	necessary thermal energy (kW)	necessary thermal energy per month (kW·h)
Jan.	31	–4.6	40.5	45.1	8.3	6.202	8.0	5.967
Feb.	28	–2.0	40.5	42.5	7.9	5.279	7.6	5.079
Mar.	31	2.4	40.5	38.1	7.0	5.240	6.8	5.041
Apr.	30	7.7	40.5	32.8	6.1	4.365	5.8	4.200
May	31	10.9	40.5	29.6	5.5	4.071	5.3	3.916
Jun.	30	16.2	40.5	24.3	4.5	3.234	4.3	3.111
Jul.	31	19.7	40.5	20.8	3.8	2.860	3.7	2.752
Aug.	31	16.1	40.5	24.4	4.5	3.356	4.3	3.228
Sep.	30	10.7	40.5	29.8	5.5	3.966	5.3	3.816
Oct.	31	5.8	40.5	34.7	6.4	4.772	6.2	4.591
Nov.	30	3.9	40.5	36.6	6.8	4.871,	6.5	4.686
Dec.	31	–5.1	40.5	45.6	8.4	6.271	8.1	6.033
Sum						54.487		52.420
Average					6.2	4.541	6.0	4.368
Maximum					8.4	6.271	8.1	6.033
Minimum					3.8	2.860	3.7	2.752
Min. temp. (°C)		–20.0	40.5	60.5	11.2		10.8	

Figure 1 shows the losses of thermal energy through the roof and to the ground of the: a) primary fermenter b) secondary fermenter.

The determination of the losses of the thermal energy through the membrane of the primary fermenter:

$$Q_o = K_o \cdot A_o \cdot \Delta T \tag{4}$$

where:

K_o = 0.41 W/(m^2·K) (the coefficient of the passing through of the thermal energy for the external part of the wall)

A_o = 659 m^2 (the surface of the wall of the primary fermenter (the diameter of the external ring of the primary fermenter D_s = 35.0 m, H = 6 m))

ΔT (°C) – the difference of the temperatures in the primary fermenter and in the surroundings

Note: The difference is changed with the seasons and the months. The medium monthly temperature is taken.

Table 7 shows the losses of thermal energy of the membrane of the fermenter.

Table 7: Losses of the thermal energy of the membrane of the fermenter

month	days (d)	average outside temperature (°C)	fermenter temperature (°C)	temperature difference (°C)	necessary thermal energy (kW)	necessary thermal energy per month (kW·h)
Jan.	31	–4.6	40.5	45.1	12.2	9.065
Feb.	28	–2.0	40.5	42.5	11.5	7.716
Mar.	31	2.4	40.5	381	10.3	7.658
Apr.	30	7.7	40.5	32.8	8.9	6.380
May	31	10.9	40.5	29.6	8.0	5.950
Jun.	30	16.2	40.5	24.3	6.6	4.727
Jul.	31	19.7	40.5	20.8	5.6	4.181
Aug.	31	16.1	40.5	24.4	6.6	4.905
Sep.	30	10.7	40.5	29.8	8.1	5.797
Oct.	31	5.8	40.5	34.7	9.4	6.975
Nov.	30	3.9	40.5	36.6	9.9	7.119
Dec.	31	–5.1	40.5	45.6	12.3	9.166
Sum						79.639
Average					9.1	6.637
Maximum					12.3	9.166
Minimum					5.6	4.181
Min. temp. (°C)		–20.0	40.5	60.5	16.3	

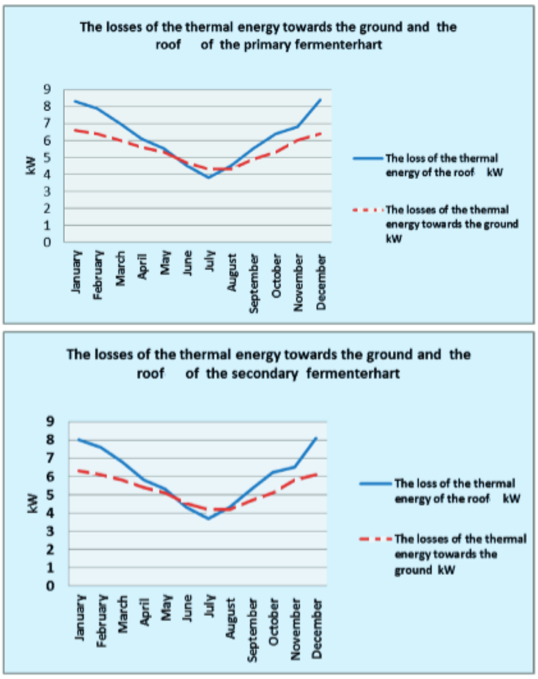

Figure 1: Losses of thermal energy of the roof and to the ground: a) primary fermenter, b) secondary fermenter

4 DISCUSSION

The determination of the necessary thermal energy for the heating of the fermenter Q_f:

$$Q_f = Q_{ps} + Q_{pp} + Q_{sp} + Q_{pk} + Q_{sk} + Q_o \quad (5)$$

where:

Q_{ps} – the necessary amount of the thermal energy for the heating of the substratum

Q_{pp} – the loss of the thermal energy through the floor of the primary fermenter

Q_{sp} – the loss of the thermal energy through the floor of the secondary fermenter

Q_{pk} – the loss of the thermal energy through the roof of the primary fermenter

Q_{sk} – the loss of the thermal energy through the roof of the secondary fermenter

Q_o – the loss of the thermal energy through the membrane.

Table 8 shows the the necessary thermal energy for heating the fermenter.

Figure 2 shows the necessary amount of the thermal energy for heating the fermenter according to the months in kW·h.

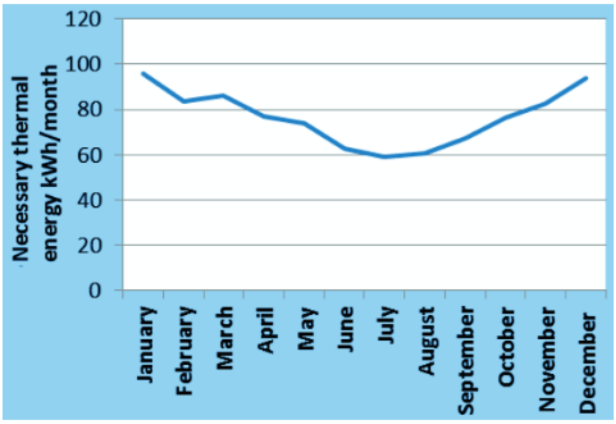

Figure 2: Necessary amount of thermal energy for heating the fermenter according to the months in kW·h

To reach the temperature of the process, from 35 °C to 40 °C, on the internal walls of the fermenter the tubes made from stainless steel DN 100 (ϕ 100 mm) for the heating will be installed, they are put alongside the wall of the fermenter until the assembly board on the edge, through which the supply and drain for the heating comes. The source of the thermal energy for the heating will be waste thermal energy from the CHP unit. From the given table it can be concluded that January and December are the months for which the most thermal energy is needed for heating the fermenter (20 % from the total of the produced thermal energy of the CHP motor), which is logical, considering the fact that these two months are the coldest. According to the given calculations, it can be concluded that there are the biggest losses through the membrane of the primary fermenter and that they can be reduced by the additional insulation of the primary fermenter.

5 CONCLUSIONS

In this paper, the required amount of thermal energy for heating a fermenter was researched, in order to maximize anaerobic fermentation and biomass utilization. It is most profitable for the fermentation process to take place at a temperature of about 40 °C, taking into account the required amount of thermal energy for heating the fermenter and the efficiency of fermentation at a certain temperature.[26–30]

Table 8: Necessary thermal energy for heating the fermenter

month	days (d)	primary fermenter heating (kW)	secondary fermenter heating (kW)	thermal energy losses (kW)	sum (kW)	necessary thermal energy per month (kW·h)	produced thermal energy per month (motor) (kW·h)	necessary thermal energy (%)
Jan.	31	87.5	0	41.4	128.9	95.911	481 596.9	20
Feb.	28	85.0	0	39.4	124.4	83.623	434 990.7	19
Mar.	31	80.1	0	35.9	116.0	86.304	481 596.9	18
Apr.	30	75.2	0	31.8	107.0	77.034	466 061.5	17
May	31	70.2	0	29.1	99.3	73.888	481 596.9	15
Jun.	30	62.8	0	24.6	87.5	62.982	481 596.9	14
Jul.	31	57.9	0	21.7	79.6	59.227	466 061.5	12
Aug.	31	57.9	0	24.0	81.9	60.922	481 596.9	13
Sep.	30	65.3	0	28.5	93.8	67.524	466 061.5	14
Oct.	31	70.2	0	32.3	10.5	76.289	481 596.9	16
Nov.	30	80.1	0	34.9	115.1	82.837	466 061.5	18
Dec.	31	85.0	0	41.4	126.4	94.042	481 596.9	20
Average (kW)		73.1	0	32.1	105.2			16
Sum (kW·h)						920.582	5 670 414.8	

Based on the predicted energy requirements, low energy was required to operate the anaerobic digesters in June through August, the lowest being in July and more energy was required in November through March. Monthly energy requirements were higher and relatively consistent from November through March because of the frozen ground.

Based on the research results, it can be concluded that an average of 16 % of the produced CHP engine heat is needed annually to heat the fermenter. The highest amount of thermal energy is needed in January and December, about 20 %, and the lowest in July, 12 %. The remainder of thermal energy can be used for the needs of some production processes or for space heating, in order to maximize the efficiency of the biogas plant.

Significant energy could be saved if the waste manure heat is used for heating the input mass before it goes into the fermenter. Reduction of thermal energy consumption for heating fermenter can be achieved by additional insulation of the fermenter, in order to reduce losses. It is necessary to calculate additional investments for the insulation of fermenters during the construction of the facility and determine the time period for which the invested funds would be returned.

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