TEKA. COMMISSION OF MOTORIZATION AND ENERGETICS IN AGRICULTURE – 2015, Vol. 15, No. 1, 83–88

Design of Digester Biogas Tank
Part 2: The Design Process of Digester Biogas Tank

Karol Tucki, Marek Klimkiewicz, Piotr Piątkowski

Department of Production Management and Engineering, Warsaw University of Life Sciences – SGGW

Received January 09.2015; accepted February 19.2015

Summary. The paper describes the design process of digester biogas tanks.The analysed issues include:the construction assumptions related to construction of the biogas tank shell, design of the roof, the thermal insulation, the selectionof inlet and outlet pipes used for the substrate transport.
Key words: biogas, calculation, project.

INTRODUCTION

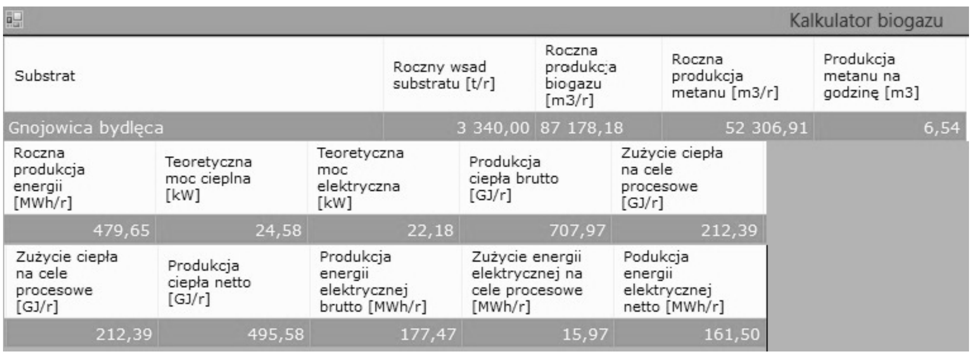
Fermentation tank is the central part of any biogas plant. It is there that the input material (substrate) is broken down and biogas is produced. In order to create a design for a fermentation chamber a number of assumptions must be made including the type and quantity of substrates used and the installation type. On the basis of the above-mentioned data, it is necessary to assess the efficiency of a biogas energy plant [9, 10]. A number of additional assumptions must also be made in relation to the finishing elements of the tank. The digester biogas tanks may be manufactured from sheet metal, ferro-concrete, plastics. They are mostly cylindrical in shape, may be submerged in soil, free-standing or placed horizontally on foundations [2].

THE INITIAL DESIGN ASSUMPTIONS OF THE DESIGNED BIOGAS PLANT

The analyzed design of a digester biogas tank shall be intended for a biogas plant located on the premises of an agricultural farm dealing with cattle production. The farm shall, instead of storing it in a tank, use the manure in the proposed digester biogas tank and process it into biogas. It was assumed that the farm owned 200 animals. The substrate for biogas production is cattle slurry. The operation of the biogas plant will be based on a single-stage technology, mesophilic (35°C) utilizing wet fermentation. The fermentation chamber was designed as a vertical one with a biogas tank in the form of a roof membrane [3, 6]. Sometimes other design philosophies for biogas tanks are utilized, e.g. gas cushions [4].

CALCULATION OF ENERGY YIELD

Calculations of the quantity of methane produced and the energy yields were realized using the designed calculator (Fig. 1).


Kalkulator biogazu

Substrat	Roczny wsad substratu [t/r]	Roczna produkcja biogazu [m3/r]	Roczna produkcja metanu [m3/r]	Produkcja metanu na godzinę [m3]
Gnojowica bydlęca	3 340,00	87 178,18	52 306,91	6,54

Roczna produkcja energii [MWh/r]	Teoretyczna moc cieplna [kW]	Teoretyczna moc elektryczna [kW]	Produkcja ciepła brutto [GJ/r]	Zużycie ciepła na cele procesowe [GJ/r]
479,65	24,58	22,18	707,97	212,39

Zużycie ciepła na cele procesowe [GJ/r]	Produkcja ciepła netto [GJ/r]	Produkcja energii elektrycznej brutto [MWh/r]	Zużycie energii elektrycznej na cele procesowe [MWh/r]	Podukcja energii elektrycznej netto [MWh/r]
212,39	495,58	177,47	15,97	161,50

Fig. 1. Calculation of biogas yield in the designed plant [own elaboration]

DETERMINATION OF LOAD VOLUME IN THE FERMENTATION TANK

When choosing the size of the fermentation chamber the aim is not to achieve a total decomposition of the organic material in order to maximize biogas production. This would require a very long storage of substrate in the chamber and therefore the need for extremely large tanks [7]. In order to verify the resultant volume of the fermentation chamber it is necessary to determine its volume load parameter, which informs what quantity of dry organic mass (d.o.m.) should be fed for every square meter of the chamber's volume. This parameter is also used in order to estimate the optimal biogas production [1, 11]. It is calculated using the following equation (1).

$$B_R = \frac{m \cdot s.m.o.}{V_{wkf.}}, \quad (1)$$

where:
B_R – volume load [kg d.o.m./m³/d],
d.o.m. – content of dry organic mass in dry organic mass [%],
m – quantity of substrate fed in a given time unit [kg/d],
V_{wkf} – initial volume of fermentation chamber [m³].

Another parameter that should be taken into consideration when planning the reactor's size is the hydraulic retention time. Its value determines the number of days the substrate should stay in the fermentation chamber to decompose [Curkowskii in. 2009, Scholwin]. It is calculated using the equation (2).

$$HRT = \frac{V_{wkfw}}{V}, \quad (2)$$

where:
HRT – hydraulic retention time [days],
V_{wkf} – initial volume of fermentation chamber [m³],
V – volume of substrate [m³].

In order to calculate the B_R and HTR parameters, a few variants of the fermentation chamber's size should be considered. The value of B_R and HTR were calculated using equations (1) and (2). Calculation results were given in the table below (Table 1).

Table 1. Calculated HRT and B_R values for different fermentation chambers

Chamber's volume – [m³]	Volume load – B_R [kg d.o.m./m³/d]	Hydraulic Retention Time – HTR [d]
100	78,5	10
150	52,3	15
200	39,3	20
250	31,4	25
300	26,2	30
350	22,4	35
400	19,6	40
450	17,4	45
500	15,7	50
550	14,3	55
600	13,1	60
650	12,1	65
700	11,2	70
750	10,5	75
800	9,8	80
850	9,2	85
900	8,7	90
950	8,3	95
1000	7,9	100

Sorce: own elaboration

On the basis of results presented in the table (Table 1) there was created a graph (Fig. 2) which presents the relation between the volume load and the hydraulic retention time. The highest biogas production is achieved for the volume read at the crossing point of B_R and HTR lines. The graph shows that a threshold value for rector's volume is 300 m³. Above this value the volume load decreases and the retention time increases. For the analyzed project the optimal value was assumed at 250 m³.

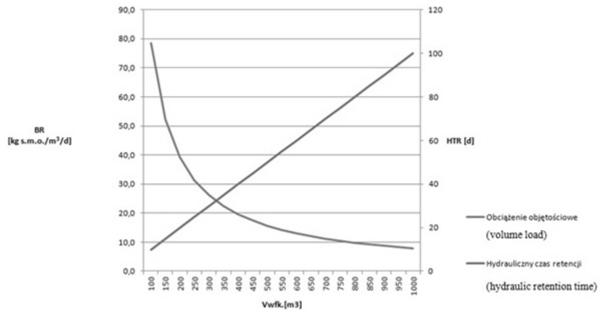


Fig. 2. Relation between volume load and hydraulic retention time [own elaboration]

CALCULATION OF FERMENTATION CHAMBER'S VOLUME

The reactor's volume was calculated using equation (3), taking into consideration the volume needed for heating installation, stirrer and roof construction.

$$V_{wfk} = \frac{M_{sub}}{\rho_{sub}} \cdot T_r \cdot 1{,}25, \quad (3)$$

where:
M_{sub} – substrate mass stream [kg/d],
ρ_{sub} – specific density of substrate [t/m³],
T_r – period of fermentation of substrate in the chamber [d],
1,25 – volume ratio for the accompanying equipment.

The height/diameter ratio should be: $\frac{h}{d} = \frac{1}{2}$, therefore h = r. The chamber's volume, calculated on the basis of equation (3), was used in an equation for a cylinder volume. Therefore, the radius of the cylinder was calculated – r, which is, at the same time, the height of the chamber – h; and next the chamber's diameter was calculated – d.

ASSUMPTIONS RELATED TO THE SHELL OF THE TANK

A steel construction was assumed, as steel tanks are more resilient to biogas and substrate leakages in comparison to ferro-concrete chambers. The idea to use steel prefabricated units is also supported by the fact that it allows for quick and simple reactor production [8]. The designed tank may be delivered in a number of parts that will be connected at the destination. The installation is realized by connecting finished rings from bottom to top using hydraulic lifts.

Due to lack of publicly available information on the design of fermentation chambers for biogas plants, the thickness of walls and the bottom of the tank are calculated using norm PN-B-03210 which covers construction of steel tanks for liquids.

According to the PN-B-03210 norm, the tank should consist of six bands of shell (Fig. 3) joined using groove welds.

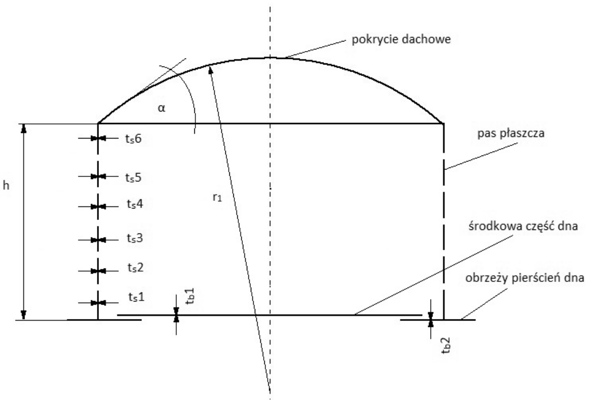


Fig. 3. Schematic construction of a reactor [PN-B-03210]

The shell of the tank was divided into 6 equal bands. According to the norm PN-B-03210, the shell of the tank should be produced from unalloyed steel. Therefore, the material chosen for production may be unalloyed steel St3SX chosen from the PN-B-03200 norm. Calculation of thickness of individual bands connected by groove welds were realized according to the PN-B-03210 norm and equations (4) and (5). Thickness of steel sheets ($t_{s,e}$), in millimetres, of individual bands of the shell is established by selecting the largest values obtained from:

– exploitation condition expressed by equation (4):

$$t_{s,e} = \frac{(\gamma_{fn}\rho_n + \gamma_f \rho_C y)\gamma_n r}{f_{dT}\alpha_\perp} + C_1, \quad (4)$$

– hydrostatic test condition expressed by equation (5):

$$t_{s,e} = \frac{(\gamma_{fn}\rho_n + \gamma_f \rho_w y)\gamma_n r}{f_{dT}\alpha_\perp}, \quad (5)$$

where:

ρ_n – computational overpressure in the gas space of the tank with a fixed roof or weight (own) of a floating roof divided by the tank's cross-section area (with a tank with fixed roof with hydrostatic test =0), with exploitation conditions = 100 [kPa],

y – distance from the upper edge of the shell (in case of a floating roof – from the maximal liquid level) to level: 100 mm over the bottom edge of a dimensioned shell band, when it is connected via groove weld or 300 mm in case of a band connected via end-jointing [m];

C_1 – corrosion allowance [PN-B-03210],

$\alpha_\perp$ – should be assumed =1 [PN-B-03200],

γ_f – load coefficient [PN-B-03210],

γ_{fn} – pressure load coefficient in the gas area of the tank with overpressure [PN-B-03210],

γ_n – destruction consequence coefficient for hazardous and flammable liquids [PN-B-03210],

f_{dT} – , f_{dT} steel design strenght, 250 MPa, value for St3SX steel chosen from [PN-B-03200],

ρ_c, ρ_w – weight by volume of liquid (stored) [kN/m³],

r – tank's diameter in [mm].

The shell should not be produced from sheets thicker than 40 mm [13, 14]. The performed calculations, after rounding to full mm, provided the following thickness for the rings (Table 2).

Table 2. Calculated thickness of individual rings for the tank's shell [own elaboration]

Shell ring	Thickness [mm]
tse1	6
tse2	6
tse3	6
tse4	6
tse5	5
tse6	5

The internal surface of the shell will be coated with epoxy cover Breston CE100, which will serve as a chemical and anti-corrosion protection. In order to monitor all spills of hazardous substances into the environment, the external surface of the shell will utilize a spill monitoring system Breston MPV345 [breston.pl/zabezpieczenia-chemoodporne-stal.php]. The top ring will be capped with an angle section 100x100x7 manufactured from the same steel as the rest of the shell. The thickness of the middle section of the tank's bottom (t_{b2}) was assumed on basis of [PN-B-03210] and will be 5 mm and the thickness of the ring connecting the middle part of the tank's bottom with the tank's shell (t_{b1}) will be 6 mm.

ROOF OF THE DESIGNED TANK

The covering of the tank will be a gas-tight membrane, which will serve as a biogas tank. In order to protect the gas against weather conditions, the gas-tight membrane will be covered by an additional external membrane. Air will be pumped between the two membranes. The basic characteristics of the two membranes are presented in Table 3.

Table 3. Parameters of roof membranes [www.czystaenergia.pl]

Parameter	**Polyester – internal load-bearing layer**	**PVC – external covering layer**
Unit weight	900 g/m2	900 g/m2
Maximal tearing strength	4700 N/5cm	4200 N/5cm
Maximal puncture strength	4500 N/5cm	4000 N/5cm
Gas permeability (Methane)	< 200 (cm3/(m2 d bar)	< 450 (cm3/(m2 d bar)
Fire rating DIN 4102	B1	

Both membranes will be attached to the angle section topping the tank, between the internal membrane and the applied angle section there will be a seal of foamed EPDM rubber [www.essentracomponents.pl]. The capacity of the gas membrane should be from ¼ to 2 daily biogas yields. The project assumes that the biogas tank with the part of the fermentation chamber not filled with substrate will be able to hold ½ of a daily biogas production. Annual production of biogas read from the calculator is about 87 178.18 m^3/y and the operating time of the biogas plant is 8000 hours a year, i.e. about 333 days. The daily production of biogas will therefore be about 262 m^3. According to the literature sources [12] biogas tanks are designed to store ¼ to 2 daily biogas production. The project assumes that the tank should be able to hold ½ of the daily biogas production. Part of the gas is going to fill the part of the tank not filled with substrate.

The height of the membrane dome was established using system of equations (6). The first equation covers the volume of a hemispherical bowl and the second is the equation for the radius of the hemispherical bowl's base:

$$\begin{cases} V_{mw} = \pi h^2 R - \frac{\pi}{3} h^3 \\ r_{mw} = \sqrt{(2R-h)h} \end{cases}, \quad (6)$$

where:
V_{mw} – volume of internal membrane that stores gas [m^3],
h – height of the internal membrane that stores gas above the tank [m],
r_{mw} – internal diameter of the angle section to which the membrane is attached [m],
R – diameter of the sphere out of which the hemispherical bowl is cut [m].

TANK'S THERMAL INSULATION

The selected insulation material is a mat of mineral glass wool, 10 mm thick, with thermal transmittance of 0.044 W/m^2 which will be glued to the shell using SPRAY-KON S202 glue. The insulation will be additionally covered with a trapezoidal profiled steel sheet FLOLINE 40, which will protect the tank against weather conditions. The sheet will be connected to the channel sections using sheet metal screws. Both channel sections and the screws will be selected using the software in which the project will be created (e.g. Autodesk Inventor 2014).

SELECTION OF PIPES TO FEED AND REMOVE THE SUBSTRATE

The substrate (cattle slurry) will be pumped to the tank via a feeder pipe located above the fluid level. The slurry will be pumped from the fermentation tank to a post-fermentation tank via an exit pipe located in the middle part of the lower ring of the chamber. The diameter of the pipe was calculated after the conversion of equation (7):

$$Q = A \cdot V, \quad (7)$$

where:
Q – daily substrate flow [m^3/s],
A – pipe's cross-section area [m^2],
V – substrate flow speed [m/s], [5].

Daily substrate flow Q was calculated using equation (8):

$$Q = \frac{Msub}{q}, \quad (8)$$

where:
M_{sub} – substrate mass stream [kg/d],
q – density of substrate [kg/m^3].

On the basis of calculations the value of Q was achieved at 10 [m^3/d], i.e. 0.00016 [m^3/s]. When substituting and transforming equation (7), the target pipe's cross-section area was calculated. Next, after using the equation for an area of a circle, the pipe's diameter was calculated. From catalogue [6] a pipe of stainless steel was chosen with similar internal diameter of 57 mm and thickness of 2 mm. It was assumed that the substrate will be fed from the tank using identical pipe.

CONCLUSIONS

The optimal volume of a fermentation chamber is impacted by a number of factors such as: volume load, hydraulic retention time and the coefficient of the space required by the technical equipment. The construction elements have, to a large extent, been determined.

The realization of full calculations and detailed selection of elements requires knowledge of many disciplines such as: thermal engineering, liquid mechanics or mechanics and mechanics of materials.

REFERENCES

1. **Curkowski A., Mroczkowski P., Oniszk-Popławska A., Wiśniewski G., 2009:** Biogaz rolniczy – produkcja i wykorzystanie, Mazowiecka Agencja Energetyczna. Warszawa.
2. **Curkowski A., Oniszk-Popławska A., Wiśniewski G., 2011:** Mała biogazownia rolnicza z lokalnym zagospodarowaniem ciepła odpadowego i masy pofermentacyjnej. FundacjaInstytutnarzeczEkorozwoju, Warszawa.
3. **Fischer T., Krieg A., 2002:** Projektowanie i budowa biogazowni, Krieg& Fischer GmbH, Germany.
4. **Fleszar J., Kalinowska K., 2013:** Rodzaje zbiorników do magazynowania biogazu stosowanych w biogazowniach. TechnikaRolniczaOgrodniczaiLeśna. Nr 2, 20-22.
5. **Gradziuk P. i inni., 2003:** Biopaliwa, Wydawnictwo Wieś Jutra, 54-58.
6. **Kowalska A., 2011:** Recruiting and using agricultural biogas, TEKA Kom. Mot. Energ. Roln, Lublin, Vol. 11c, 118-125.
7. **Myczko A., Myczko R., Kołodziejczyk T., Golimowska R., Lenarczyk J., Janas Z., Kliber A., Karłowski J., Dolska M., 2011:** Budowa i eksploatacja biogazowni rolniczych. InstytutTechnologiczno-Przyrodniczy, Warszawa-Poznań.
8. **Piekarczyk M., Michałowski T., Kowalczyk D., 2014:** Przykłady projektowania stalowych konstrukcji

powłokowych według Eurokodów. ZK2014 – Konstrukcjemetalowe/Metal Structures, Kielce-Suchedniów, Poland, 1-4.
9. **Roszkowski A., 2006.:** Agriculture and fuels of the future, TEKA Kom. Mot. Energ. Roln., Vol. 6, 131-134.
10. **Schenkel Y., Crehay R., Delaunois C., Schummer J., 2003.:** The agricultural sector and bioenergy production. TEKA Kom. Mot. Energ. Roln, Lublin, Vol. 3, 228-235.
11. **Scholwin F. i inni, 2006:** Biogaz – Produkcja i wykorzystanie, InstitutfürEnergetikumwelt GmbH, 1-176.
12. **Szlachta J., 2006:** Możliwości pozyskania biogazu rolniczego jako odnawialnego źródła energii, 1-32.
13. **Ziółko J., Włodarczyk W., Mendera Z., Włodarczyk S., 1995:** Stalowe konstrukcje specjalne. Arkady, Warszawa.
14. **Ziółko J., 1986:** Zbiorniki metalowe na ciecze i gazy. Arkady, Warszawa.
15. PN-B-03210: 1997 Konstrukcje stalowe. Zbiorniki walcowe pionowe na ciecze. Projektowanieiwykonanie.
16. www.askotech.com.pl/produkt_08_122.html -katalog rur.
17. www.czystaenergia.pl/pdf/biogazexpo2013/14a.pdf.

PROJEKTOWANIE ZBIORNIKA KOMORY BIOGAZOWEJ CZ. 2.: PROCES PROJEKTOWANIA KOMORY FERMENTACYJNEJ

Streszczenie. Opisano proces wyznaczania parametrów geometrycznych komór biogazowych. Przeanalizowano założenia konstrukcyjne odnoszące się do budowy płaszcza zbiornika biogazowego, rozwiązanie konstrukcji dachowej projektowanego zbiornika, izolację termiczną zbiornika oraz dobór przewodów doprowadzającego i odprowadzającego substrat wykorzystywany do produkcji biogazu.
Słowa kluczowe: biogaz, obliczenia, projekt.