ON THE ISSUE OF HEAT EXCHANGE IN A BIOGAS INSTALLATION

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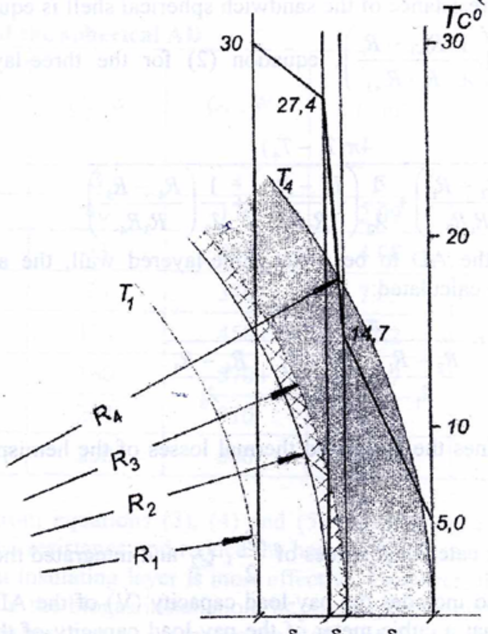
Abstract. The heat balance of biogas installations widely used on farms is studied. Heat losses through the shell of the anaerobic digester (AD) are considered in approximation to a spherical wall and under the conditions of natural convection without taking into account the effect of the thermal boundary layer. It is shown that heat losses increase proportionally to the surface area of the AD and the amount of evolved gas increases proportionally to the capacity. As a result, with the increase of the AD size the fraction of heat losses in relation to the energy of produced biogas decreases, tending asymptotically to zero. For installations of different capacity, the amount of energy which is necessary for sustaining the mesophilic process of anaerobic fermentation of organic wastes was determined.

Keywords: biogas installation, anaerobic digester, heat exchange.

A fixed-dome type of the anaerobic digester (AD), which is most widely used for biogas production on small farms, involves anaerobic fermentation of organic wastein a gas-tank buried in the ground – the shape of which can be approximated to a hemisphere with a flat basis[1].

The output of the biogas installation to a large extent depends on the temperature in the AD. The maximum output of biogas is achieved under thermophilic conditions (55-60^{0}C). However, for small custom-made installations even sustaining of the mesophilic process (30-35^{0}C) represents a difficult task, especially under cold climatic conditions, when air temperature in the winter can be as low as -20^{0}C. At low temperatures calorification (the phycophilic process) of biogas drops significantly, necessitating the external energy supply to increase the output of the installation.

The purpose of this paper is the investigation of the heat exchange process in the biogas installation and rating of biogas yields (or equivalent energy) consumption of which is necessary for compensation of heat losses through the walls of the AD and for sustaining of the mesophilic mode in the bioreactor.



The diagram of a three-layered spherical wall

For reducing the heat transfer, the walls of the AD are insulated with a convection-resistant material (foam plastic, perlite mixture, aerated concrete, etc.) and are plastered. At direct contact of the structure of the AD, with the ground, the heat transfer process intensifies through the mass transfer of moisture. To prevent this, the pit surface should be covered with a moisture-proof material (e.g. polyethylene), and the space between the AD and the ground should be filled with a dry loose material (gravel, sand, crushed stone). The shell of the AD of such a design can be regarded as a three-layered wall (Fig. 1): the thickness of the first (internal) layer is $\delta_1 = R_2 - R_1 = 0.2$ m, and it is characterized by the heat transfer factor of $\lambda_1 = 1$ W/m.deg (construction materials are blocks of different origins); the thickness of the second (heat-insulating) layer is $\delta_2 = R_3 - R_2 = 0.05$ m and $\lambda_2 = 0.05$ W/m.deg, and the thickness of the third (moisture-proof) layer is $\delta_3 = R_4 - R_3 = 0.3$ m, $\lambda_3 = 0.4$ W/m.deg; λ_i are taken from [2].

The present work deals with the calculation of the heat balance for the biogas installation of a hemispheric shape with a flat basis. Thus, it is supposed that both internal and external surfaces of the AD structure are isothermal surfaces and are characterized by stationary temperature fields. The AD is built into the ground, the temperature of which at the depth of 4 m does not fall below 5-6^{0}C during the winter. Heat irradiation from the substratum onto the internal surface of the AD takes place in the mode of natural convection. Assuming the effect of the thermal boundary layer to be negligible, it follows that the substratum temperature sustained against the internal surface of the wall is 30^{0}C, while the outer surface temperature equals the ground temperature (5^{0}C).

The heat flow through the spherical wall is formulated as follows [3]:

$$q = -\lambda \frac{dT}{dR} = -\lambda (T_2 - T_1) \frac{R_1 R_2}{R_2 - R_1} \cdot \frac{1}{R^2} \tag{1}$$

Hence, provided $T_1 > T_2$, the amount of the heat transferred in a unit time through spherical surface is:

$$Q = qF = q \cdot 4\pi R^2 = 4\pi\lambda (T_1 - T_2) \frac{R_1 R_2}{R_2 - R_1} \tag{2}$$

Assuming that the thermal resistance of the sandwich spherical shell is equal to the sum of the thermal resistance of each layer $\left(\frac{1}{\lambda_i}\frac{R_{i+1} - R_i}{R_i \cdot R_{i+1}}\right)$, equation (2) for the three-layered wall can be formulated as follows:

$$Q_1 = \frac{4\pi (T_1 - T_4)}{\frac{1}{\lambda_1}\left(\frac{R_2 - R_1}{R_1 R_2}\right) + \frac{1}{\lambda_2}\left(\frac{R_3 - R_2}{R_2 R_3}\right) + \frac{1}{\lambda_3}\left(\frac{R_4 - R_3}{R_3 R_4}\right)} \tag{3}$$

Considering the basis of the AD to be a flat three-layered wall, the amount of the heat transferred through the basis can be calculated:

$$Q_2 = \frac{\pi (T_1 - T_4) R_1^{\,2}}{\frac{R_2 - R_1}{\lambda_1} + \frac{R_3 - R_2}{\lambda_2} + \frac{R_4 - R_3}{\lambda_3}} \tag{4}$$

Sum $Q_3 = \frac{Q_1}{2} + Q_2$ determines the integrated thermal losses of the hemispherical AD $\left(\frac{Q_1}{2}\right)$ with the flat basis (Q_2).

The Table below shows the calculated values of $\frac{Q_1}{2}$, Q_2 and integrated thermal losses Q_3 for different capacity of the AD. It also includes the pay-load capacity (V) of the AD and the gas yield (Column 6). Thus, it is accepted that a cubic meter of the pay-load capacity of the AD yields about 0.3-0.5m^3 of biogas (0.017 m^3/h on average) per day. The heating value of the biogas depends on the methane percentage and changes within the limits of 21,000-25,000kJ/m^3. Having derived $\bar{q} = 23{,}000$ kJ/m^3, the energy equivalents of the evolved gas are calculated according to Column 7.

As thermal losses are proportional to the surface area of the AD, and the amount of the evolved gas increases proportionally to the capacity, the fraction of thermal losses $\frac{Q_3}{Q_0}$ in relation to the energy of the produced biogas decreases and asymptotically tends to zero when $R_1 \to \infty$ (Column 8).

This can be an encouraging factor for building large-capacity biogas installations. In addition, in large capacities it is easier to achieve the constancy of temperature and microbiological conditions, which are important for the optimum process of fermentation. It is generally accepted that the increase of 50 % in the capacity involves the increase of minimum 10% in the construction costs [4].

The calculation results listed in the Table are of practical importance for selecting a number of optimum parameters for small biogas installations and specific determination of the amount of the energy that is required for sustaining the mesophilic process under the extreme conditions described above ($\Delta t = 25°C$). In the case of the 11.5m^3 experimental biogas installation constructed by us (Artani Village, Tianeti Region), it is necessary to consume up to 40% of its output (approximately 1300W) to compensate the heat losses.

The heat flow through the spherical wall of this installation is $q_1 = \frac{Q_1}{\pi \bar{R}^2}$; the heat flow through the basis is $q_2 = \frac{Q_2}{\pi R_1^2}$, where $\bar{R} = \frac{R_1 + R_4}{2}$ is the mean radius of the AD, and values $Q_1 = 327W$ and $Q_2 = 123$ W are determined from the Table. Having derived q =12.75 W/m^2 by formula

$$T_{i+1} = T_i - q\left(\frac{\delta_i}{\lambda_i}\right), \tag{5}$$

the temperature field inside the AD shell is calculated (see the Figure).

Thermal balance of the spherical AD

R_1, m	$\frac{Q_1}{2}$, W	Q_2, W	Q_3, W	V, m^3	Amount of the evolved gas, m^3/ h	Q_0, W	$\frac{Q_3}{Q_0}$
1	2	3	4	5	6	7	8
1.0	128	40	170	2.09	0.036	230	0.75
1.25	185	63	250	4.08	0.069	440	0.56
1.5	249	90	340	7.05	0.12	770	0.44
1.75	327	123	450	11.2	0.19	1220	0.37
2.0	413	160	570	16.7	0.28	1820	0.31
2.25	506	203	710	23.8	0.40	2590	0.27
2.5	628	250	880	32.7	0.56	3580	0.25

It follows from equations (3), (4) and (5) that making each layer of the shell thicker will increase their thermal resistance and reduce the heat flow as a result. At the same time, increasing the thickness of the heat-insulating layer is most effective. However, this is connected with the increased capital investments in the biogas installation. In practice it is most expedient to thicken the moisture-proof layer by increasing the space between the slopes of the pit and the AD structure. This is feasible without incurring appreciable additional charges.

In small capacity installations ($V < 2m^3$), the energy of the evolved biogas does not cover the heat losses, and, consequently, in such bioreactors sustaining of the mesophilic mode by energy supply from external sources is not economically-efficient.

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РЕЗЮМЕ

К ВОПРОСУ ТЕПЛООБМЕНА В БИОГАЗОВОЙ УСТАНОВКЕ

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В работе рассматривается тепловой баланс биогазовых установок, широко используемых в фермерских хозяйствах. Тепловые потери через оболочку ферментера оценены в прибилжении сферической стенки в условиях естественной конвекции без учета эффекта теплового пограничного слоя. Показано, что тепловые потери увеличиваются пропорционально площади поверхности ферментера, а количество выделяемого газа растет пропорционально объему. В результате, с увеличением размеров ферментера доля тепловых потерь по отношению к энергии вырабатываемого биогаза уменьшается, асимптотически стремясь к нулю. Для установок разных размеров определено количество энергии, необходимой для обеспечения мезофильного процесса анаэробной ферментации органических отходов.

Ключевые слова: биогазовая установка, ферментер, теплообмен.