Heat loss analysis in the semi-buried anaerobic digester in Northeast Poland

Piotr Rynkowski[1,*]

[1]Bialystok University of Technology, Faculty of Civil and Environmental Engineering
15-351 Białystok, ul. Wiejska 45A, Poland

Abstract. A thermal model was used to compare an actual and a computational heat losses in an existing the semi-buried anaerobic digester (AD) during the winter season in Northeast Poland. This work is an attempt to answer the question whether the cause of the temperature decrease of the manure AD is underestimated the heat exchanger or its low efficiency. The answer to this question is important for manager to take appropriate action. Understanding the heat loss of biogas digester is important to use these technologies to produce the biogas on assumed level in cold environment - like winter in Northeast Poland. From anaerobic digester point of view, the maintaining of optimal fermentation temperature is crucial. In the current study 2-D axisymmetric steady heat transfer model was carried out to calculate heat loss of AD for a real biogas plant located in north-eastern Poland and compared with actual state.

1. Introduction

Temperature is one of the most important parameter to control the microbiological activity in the anaerobic digester. The digestion is highly dependent on manure temperature [1]. Several researches were developing heat transfer models for AD. Many models were validated in warm climate with good agreement between the predicted and field data [2]. Some of them had the theoretical predictions of slurry temperatures was within 2.6°C agreement with field data [3]. Although there are many studies that report measured manure temperature during the year [4], there is not sufficient literature-based data to produce reliable emission calculation protocols. According to Rennie, Balde, Gordon, Smith and VanderZaag [5] there is no fully developed model for predicting temporal and spatial temperature distributions within liquid manure storage.

Most anaerobic digestion systems are designed to operate in the mesophilic temperature range around 35-40°C. In cool climate, the temperature in winter is low, what leads to a low biogas production. Several heating technique were introduced to AD to obtain stable operating temperature in the digester. The solar collectors are often used with a heat exchanger immersed in the digester manure. A greenhouse-integrated biogas system is developed. The numerical model the biogas system integrated with solar collectors is presented in [6]. An analytical expression for the instantaneous thermal efficiency of a greenhouse-integrated biogas system and the instantaneous thermal loss efficiency factor

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[*] Corresponding author: p.rynkowski@pb.edu.pl

from the system for given capacity is described in [7]. For cold climate the temperature of the slurry, the biogas, membrane, wall and cover in function of solar radiation, wind velocity, ambient temperature and digester geometry are important. The simple time-dependent thermal model was presented in [8]. Wu and Bibeau [9] presented a three-dimensional steady-state model for simulating heat transfer for anaerobic digesters for cold weather conditions. There are very developed mathematical models for the prediction of the temperature distribution within the reactor under steady state conditions [10].

Compering to the south of Europe, the north-eastern part of Poland belongs to cool climate. Because of the biogas digesters are sensitive to thermal disturbances, the heating systems for biogas digester are needed to reduce temperature fluctuations and increase biogas production. Thus, knowledge the heat loss of the anaerobic digester during the year is significant. Analyzed the biogas plant located in north-eastern Poland is burned in cogeneration process to produce electricity and heat. The cogenerated hot water is also used by heat exchanger to heat anaerobic digester. In this paper, a simple mathematical model was used to calculate the heat losses for the assumed conditions. Simulated heat transfer results were compared to a one-dimensional model and validated against experimental data using an operating anaerobic digester.

2. The anaerobic digester

Analyzed biogas plant is located in north-eastern Poland (latitude 52°55’17.2”N and longitude 23°15’56.0”E), in Ryboly village. It consists of two anaerobic digesters with diameter 30 m and height 6 m (**Fig. 1**) and one anaerobic digester with diameter 32 m and height 8 m. The analyzed reactors have diameter 30 m and height 6 m. The wall are made of reinforced concrete 25 cm thick, covered 10 cm thick polystyrene. The reactor’s floor is insulated 8 cm thick polystyrene. The cover is EPDM double layer membrane about thickness 3 mm.

Fig. 1. Large-scale semi-buried digesters located in north-eastern Poland (photo of the author).

According to the biogas plant manager, the manure setpoint temperature should be at 40°C. The fluctuations in anaerobic digesters during 2016 year changing are from 35.7°C to 43.2°C for digester nr 1 and 37.5°C to 41.3°C for digester nr 2 (**Fig 2**). During the summer the setpoint is reached and can be exceeded in hot days. During the winter the temperature is below setpoint 40°C. According to the biogas plant manager, in cool days biogas production is much lower. Temperature fluctuations in the digester should be as small as possible, less than 2–3°C for mesophiles [11]. Therefore, the thermal analysis of the anaerobic digester is required to take appropriate action.

The measuring system consists of the temperature, electricity and heat meter. Part of the data are recorded and part of them are saved manually. The data were obtained from biogas plant manager. The analyzed data are:

- water temperature at the inlet and at the outlet of the heat exchanger, for fermenters heating purposes,
- the flow rate of water by the heat exchanger,
- the digestate temperature, measured once a day,
- thermal energy generated in a cogeneration unit.

These data, taking into account the power for the heating of the supplied substrate, allow to determine the thermal power necessary to cover the heat loss by digester.

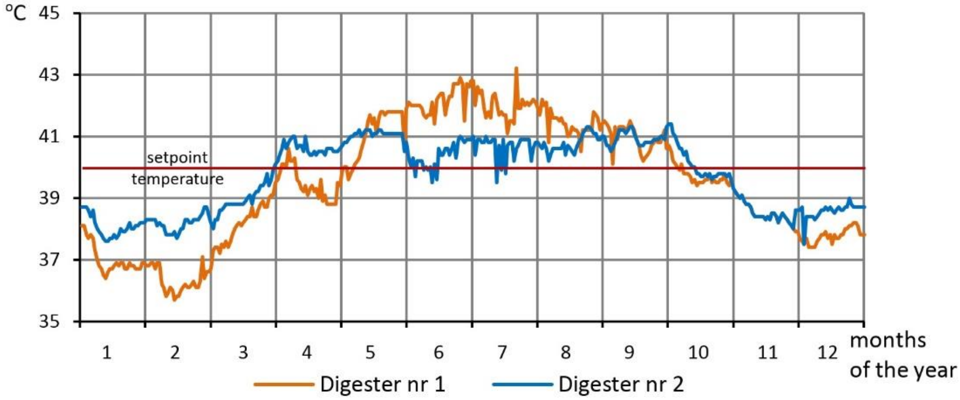

Fig. 2. The manure temperature fluctuations in anaerobic digesters 2016 year (the biogas plant data).

3. Heat transfer model

3.1. General assumptions

General assumptions are:

- heat flow through the digester is axisymmetric 2-D and steady,
- the internal heat generation due to microbial reactions is assumed to be negligible,
- physical properties of the soil, digester material, insulation material are uniform,
- due to the low value of solar radiation in the location area of digester during the winter season, to simplify the model, the solar radiation and sky effective temperature is neglected,
- the soil temperature profile based on own research.

The used model is based on an energy balance, with accounts for the relevant heat fluxes (**Fig. 3**):

- convective heat transfer from the manure surface,
- convective heat transfer between biogas and double layer cover,
- convective heat transfer in double layer cover,
- conductive heat transfer through manure floor and wall,

The required model inputs are:

- ambient air temperature,
- digesters dimensions,
- thermophysical properties of the materials (thickness, thermal conductivity, heat capacity),
- temperature and flow rate of incoming air between double layer cover,
- soil properties (thermal conductivity).

3.2. Heat balance

According to the assumptions, the thermal balance model equation becomes (**Fig. 3**):

$$Q_{manure} + Q_{heating} = Q_{cover} + Q_{wall} + Q_{floor} + Q_{air-outlet} \tag{1}$$

where Q_{manure} is the heat required to raise temperature of the influent manure to the operating temperature, W; $Q_{heating}$ is the heat supplied by the heating system to cover heat loss, W; Q_{cover} is the heat losses through the digester cover, W; Q_{wall} is the heat losses through the digester wall, W; Q_{floor} is the heat losses through the digester floor, W; $Q_{air-out}$ is the heat losses through the digester cover by the air flow between the membranes of the cover, W.

Convection heat flow is calculated as:

$$Q = \alpha \cdot A \cdot \left(T_{sur} - T_{in}\right) \tag{2}$$

where α is coefficient of heat transfer, W/(m^{2}K); A is exchange area, m^2; T_{sur} surface temperature (K); T_{in} is temperature of inlet air or biogas, K.

Conduction heat flow is calculated as:

$$Q = \lambda \cdot A \cdot \frac{dT}{dx} \tag{3}$$

$$dx = A \cdot \frac{\left(T_{out} - T_{in}\right)}{\sum_{i}^{N} \frac{e_i}{\lambda_i}} \tag{4}$$

where e_i is wall thickness of the material i, m; λ_i is thermal conductivity of the material i, W/(m·K).
The values as below are used for the thermal conductivity:

– soil, loess	1.00 W/(m·K),
– insulation, styrofoam	0.04 W/(m·K),
– wall, reinforced concrete	2.30 W/(m·K),
– cover, membrane EPDM	0.06 W/(m·K),
– floor, reinforced concrete	2.30 W/(m·K),
– biogas, methane	0.0332 W/(m·K),
– air, between membrane	0.0242 W/(m·K).

Measured the flow rate and the water temperature at the inlet and at the outlet of the heat exchanger, for fermenters heating purposes, allow to determine the average thermal power to cover heat losses in particular months of the winter season (calculations were made for cool months: January, February, March April, October, November December). The heat rate balance for a working fluid passing through the heat exchanger was calculated according to the following **Eq.** (5), where m – mas flow rate, kg/s; c_p - specific heat, J/(kg·K); $T_{in,out}$ – temperature, respectively at inlet and outlet side, °C.

$$Q = m\, c_p \left(T_{in} - T_{out}\right) \tag{5}$$

3.3. Boundary condition

It is analysed 2-D axisymmetric heat transfer problem with Dirichlet, Neumann and Robin boundary conditions. The surface of soil column adopts the Robin boundary condition. The undisturbed ground temperature profile was obtain from own work of the author [12]. Ambient temperatures based on average monthly outdoor temperatures for a given location (**Table 1**). The manure temperature fluctuations in anaerobic digesters during 2016 year was obtain from biogas plant data (**Fig. 1**).

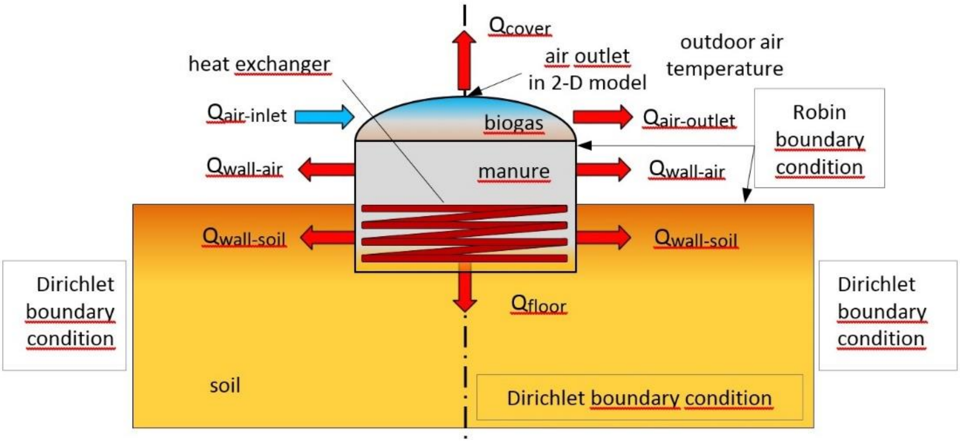

Fig. 3. Heat transfer process between anaerobic digester and surroundings with axis of symmetry 2-D axisymmetric steady heat transfer model.

3.4. Simulation method

Two dimensional axisymmetric implemented sketch model is shown on **Fig. 4**. The model was solved using Ansys(R) Fluent(R) Academic Version 16.0, computational fluid dynamics (CFD) simulation software. Simple scheme for pressure velocity coupling were solved. The second order upwind scheme were used for energy discretization. The realizable k-ε turbulence model was adopted with scalable wall functions. For each simulation solution was converged before 2000 iterations.

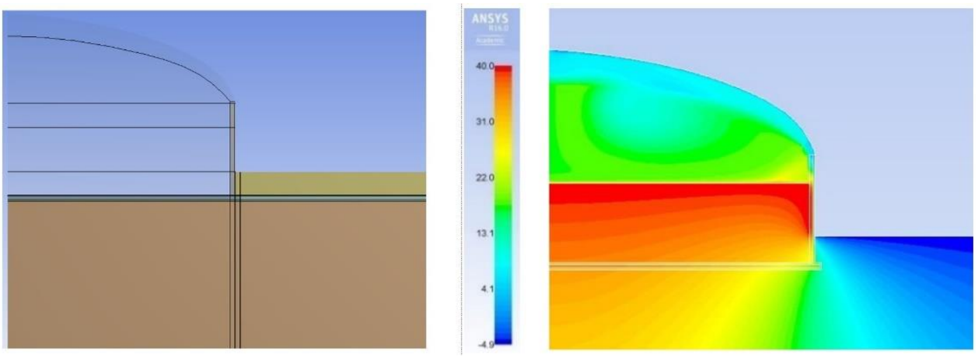

Fig. 4. 2-D axisymmetric schematic depicting digester model (left figure) and the sample temperature distribution for the coldest month – January (right figure).

As boundary condition was set average monthly temperatures in the considered area in winter season. Independently from numerical simulation heat losses were calculated using one dimensional heat transfer.

4. Results and discussion

The numerical values for heat flux at different components of the digester shows the heat flux of the cover is the largest. The heat flux by the cover is about five times more than of the wall and near forty times than of the floor, for the minimal calculation temperatures (-22)^{o}C. Taking into account the convective heat transfer associated with the air flow between double layer of membrane causes an increase the heat loss near 40% (**Fig. 5**). However, it can be concluded that neglecting convective heat transfer through the cover (as it is in the case of engineering calculations, according to the [13]) can lead to an oversizing the heat flux. Difference between the heat flux by the cover derived from numerical calculations and 1D calculations is about 17%. It results from the adopted constant value of thermal resistance of the air layer on the whole surface of the cover for 1D calculation. In fact, the distance between the membranes reaches up to 1 m at the top of the cover.

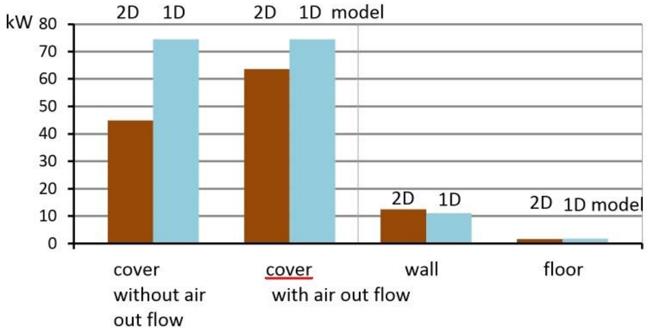

Fig. 5. The numerical values for heat flux at different components for 2D and 1D model for ambient temperature (-22)^{o}C, with and without air flow between layers of cover.

Based on measurement data and dependencies (**Eq. 5**) the average thermal power of the exchanger to cover heat losses the AD was calculated. The results, taking into account the results of numerical calculations, present **Fig. 6**. It is noticeable, a relatively large difference in the power transferred by the heat exchangers to the digesters, with comparable factor flows and temperature parameters (as it was mentioned in point 2, the geometric dimensions of the reactors are the same). For example, for the January and February the difference is near 50%. Only in March the power transmitted by the heat exchanger in digester nr 2 was lower than in digester nr 1. Compering numerical simulations to measurement data, there is a large convergence to the heat losses in digester number 1 (**Fig. 6**). In the coldest months, January, February and December the differences between the actual and theoretical values are respectively 1%, 5% and 6%. Less convergence in the remaining months is the result of the higher share of solar radiation in total heat losses. In northeast Poland, the months January, October and December months are characterized by low solar radiation. Neglecting the solar radiation during these months in total heat losses do not generate large discrepancies between the actual and theoretical state. In the summer months the solar radiation has to be included to numerical model.

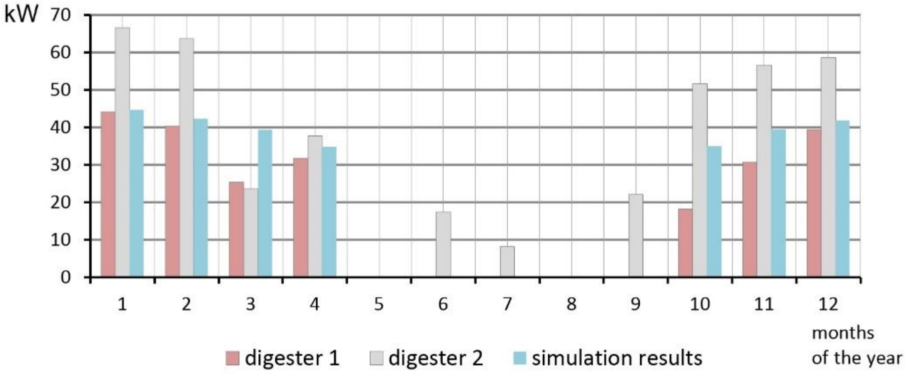

Fig. 6. The distribution of the digesters heat losses during winter season (January, February, March, April, October November December).

The biogas digester number 2 has less temperature fluctuations of the manure during the winter (**Fig. 2**). One of the reason is more energy supplied from the heat exchanger to cover heat losses (**Fig. 6)**. Based on the numerical model, it can be concluded that the power of the heat exchangers should cover heat losses for the average monthly temperatures assumed (the calculated temperature in the area of analyzed biogas plant is (-22)ºC) for AD number 2 and the manure temperature in that anaerobic digester should be near constant. The necessary thermal power of the heat exchanger for the biogas digester number 1 is not much below the required values to cover the necessary heat loss. It can increase temperature fluctuations of the manure. For October, November and December the average underestimation is respectively 48%, 22% and 6%. It should be added, it does not have to be related to underestimation of the heat exchanger itself, but its operating conditions. One of the reason may be increased thermal resistance in the surroundings of the heat exchanger, where the influence of the mixer is minimal. This is evidenced by the smaller temperature difference between the supply and return from the heat exchanger the digester nr 1 (**Fig. 7**).

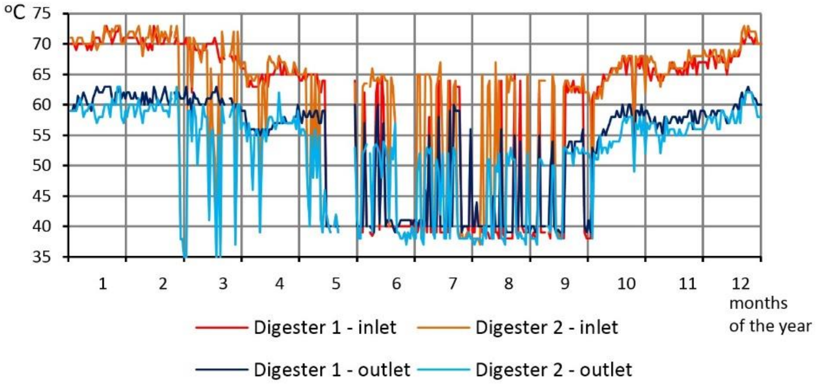

Fig. 7. The temperature at the inlet and outlet of the heat exchangers in anaerobic digesters in 2016 year (the biogas plant data).

5 Conclusion

The conclusion is as follows:

- the power of the heat exchanger cover heat losses for the average monthly temperatures for digester nr 2,
- greater temperature fluctuations of the manure the digester number 1 during the winter season is caused by minimal underestimation of thermal power (mainly October, November, December, **Fig. 6**),
- the energy received by digester number 1 is below the required value (unheated the manure, high thermal resistance in the area of the heat exchanger), the heat conduction process in the surroundings of the heat exchanger in the anaerobic digesters should be analyzed in that case.

In future study, the numerical model should be supplemented by modeling of the cover heat gain from solar irradiation and modeling of the heat absorption/production by endothermic/exothermic chemical and biochemical reactions occurring in the digestate.

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