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NUMERICAL MODELLING OF HEAT LOSS THROUGH THE COVER IN THE ANAEROBIC DIGESTER

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ABSTRACT: Anaerobic digestion is the biological degradation of biomass in oxygen-free environments. The main product of this process is biogas, rich in CH4 and CO2. Understanding the heat loss characteristic of biogas digester (BD) is important to put these technologies into application. Biogas digester may obtain assumed gas production in cold environmental when the optimal fermentation temperature is maintained. It requires heating system and insulation technologies. Here 2-D axisymmetric steady heat transfer model coupled with surrounding soil was built to calculate heat loss of HBD for a real biogas plant located in north-eastern Poland. A sample to determine the effect of air flow between the membranes of the BD cover on the heat losses has been presented.

KEY WORDS: anaerobic digestion, heat loss

Introduction

Anaerobic digestion is the biological degradation of biomass in oxygen-free environments. Biogas digester has emerged as a successful and promising technology for organic waste management. It has established process for organic wastes. The main product of this process is biogas, rich in CH_4 and CO_2. Biogas digesters (BD) may achieve higher gas production in cold environments by heating and insulation technologies. Understanding the heat loss characteristic of BD is important to put these technologies into application.

Large-scale anaerobic digestion, biogas is burned in cogeneration process to produce electricity, generally for sale and heat. The cogenerated hot water is used by heat exchanger to heat anaerobic digester. In order to maintain the operating temperature in the BD in its optimum from about 40^{o}C to 50^{o}C in the cool climate additional thermal energy is required. Biogas digesters is sensitive to thermal disturbances. Fluctuations of temperatures may lead to decreasing in the biogas yield. The heat transfer phenomena between the biogas digester situated in north-eastern Poland and its surrounding is analysed. The numerical model predicts the heat loss through the cover and the BD for different conditions in the winter season in Poland.

In tropical climate the BD can run efficiently during all year. In cool climate, the temperature in winter is low, what leads to a low biogas production. Several heating technology were introduced to BD and several models for predicting the variations of the digester temperature as a function of climatic conditions were presented (Singh, Singh, Bansal, 1985; Usmani, Tiwari, Chandra, 1996; Perrigault et al., 2012).

Heat transfer phenomena depends on ambient conditions: air temperature, wind speed, solar irradiation intensity, initial ground temperature, etc. Full CFD simulations of anaerobic digesters with non-Newtonian character of the BD are extremely complex. Nowadays CFD simulations of full-scale reactors during the long time require unaffordable computation times. Literature presents 0D thermal models which are much more efficient computationally.

An overview of literature

Singh et al. (1985) proposed a time-dependent, one dimensional model for simulating a solar-heated anaerobic digester. The solar collectors are coupled to a heat exchanger immersed in the digester manure. A fixed dome and floating dome type digesters were analyzed. The model assumed that the majority heat transfer occurs between the top of the cover and the ambient air.

Usmani et al. (1996) developed an analytical expression for the instantaneous thermal efficiency of a greenhouse-integrated biogas system and the instantaneous thermal loss efficiency factor from the system for given capacity. Gebremedhin et al. (Gebremedhin et al., 2005) established a comprehensive mathematical model that predicts energy requirements to operate a plug-flow anaerobic digester at a specified temperature. The model includes the influence of solar radiation, soil temperature distribution and periodic meteorological conditions on the digester heat transfer to the surrounding soil. Nevertheless, the accuracy of these models was not proved.

Perrigault et al. (2012) used a simple time-dependent thermal model using inputs of solar radiation, wind velocity ambient temperature and digester geometry. The model outputs include temperature of the slurry, the biogas, its holding membrane, wall and cover. The model predicts the influence of geometry and materials on the performance of the digester in cold climate.

Because of the analytical limitations the numerical simulations is a better approach to study the BD heat transfer process. Wu and Bibeau (2006) presented a three-dimensional steady-state model for simulating heat transfer for anaerobic digesters for cold weather conditions. Numerical CFD heat transfer model was used to calculate the heat transfer through the cover, floor and walls. Simulated heat transfer results were compared to a one-dimensional numerical model and validated against experimental data using an operating anaerobic digester.

Yiannopoulos et al. (2008) proposed and developed mathematical model for the prediction of the temperature distribution within the reactor under steady state conditions. The results based on model simulations performed with meteorological data, for latitudes up to 50o suggested that the proposed solar heating system could be a promising and environmentally friendly for anaerobic treatment. Bavutti et al. (2014) focused on summer overheating of BD.

Nowadays, many investigations are focused on small-scale digesters used by families to produce biogas for cooking and heating.

The current study investigates heat transfer phenomena in a large-scale semi-buried agricultural digester located in north-eastern Poland (figure 1). Two-dimensional axisymmetric numerical model was developed to simulate the heat loss as a function of climatic conditions.

Figure 1. Large-scale semi-buried digester located in north-eastern Poland
Source: author's own work.

The anaerobic digester

Anaerobic digester and heat transfer model basic components are shown in figure 2. The biogas plant is located in north-eastern Poland (latitude 52°56'N and longitude 23°15'E). It consists of two anaerobic digesters with diameter 30 m and height 6 m and one anaerobic digester with diameter 32 m and height 8 m. In study, the analyzed reactor has diameter 30 m and height 6 m. The wall is made of reinforced concrete 25 cm thick. The reactor's floor is insulated 8 cm thick polystyrene. The all surface non-buried and buried, for a better thermal insulation, are covered 10 cm thick polystyrene. The reactor's cover is a deformable green EPDM double layer membrane, whose thickness is about 3 mm. The digester is equipped with a mechanical mixing system. Biogas is burned in-site in a cogeneration unit and electricity is delivered to the national grid. Cogenerated hot water is sold and used to heat the digestate through immersed helical-coil heat exchanger. The digestate temperature set point is 40^{o}C.

The reactor is poorly instrumented. The measuring system consisted 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 heat exchanger,
- the flow rate of water by the heat exchanger,
- the digestate temperature measured once a day,
- thermal energy generated in a cogeneration unit.

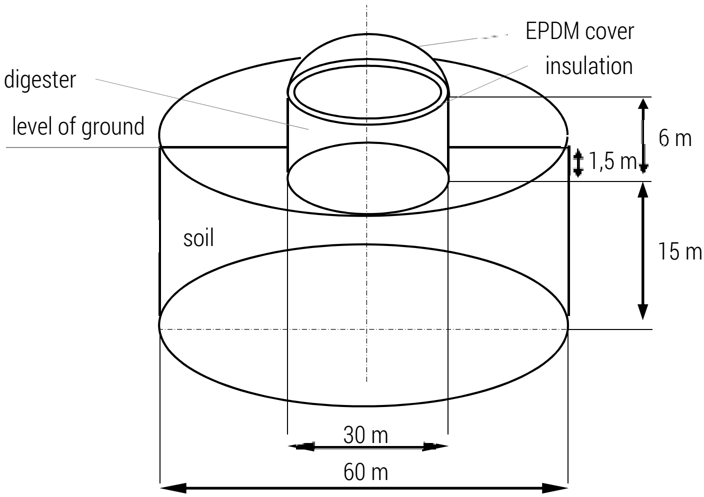

Figure 2. Schematic representation of the anaerobic digester investigated in this study (not to scale)

Source: author's own work.

The manure temperature fluctuations in anaerobic digester during 2016 year is shown in figure 3. The operating temperature fluctuates in a narrow range, between minimum 35,7°C and maximum 43,2°C. During the summer the set point is reached and exceeded in hot days. During the winter the temperature is below set point 40°C. According to the biogas plant manager, during the cool days biogas production is much lower. Therefore, the thermal analysis of the anaerobic digester is required.

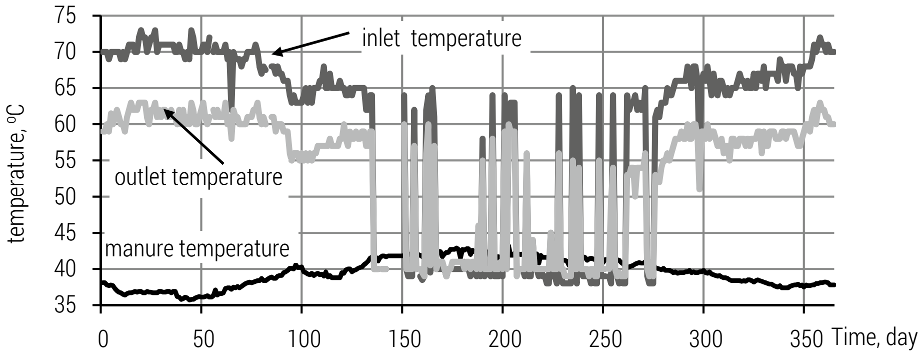

Figure 3. The manure and temperature fluctuations in anaerobic digester and temperature on inlet and outlet of the heat exchanger during 2016 year

Source: the biogas plant data.

Mathematical model

Assumptions

The assumptions used for modelling of the anaerobic digester heat transfer model:

- heat flow through the digester is axisymmetric 2-D and steady,
- the air flow between the membrane is steady,
- the ambient air temperature is constant,
- physical properties of the soil, digester material, insulation material is uniform,
- the effect of moisture transfer and phase transition on the heat transfer of the digester is ignored,
- 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 temperature profile in the soil come from own research,
- according to the biogas plant manager, heat demand for manure heating is 49.4 kW.

Thermal equilibrium equation

The thermal model equations are presented as (figure 4):

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

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 (W),

Q_{cover} – is the heat losses through the digester cover (W),

$Q_{wall\text{-}air}$ and $Q_{wall\text{-}soil}$ – is the heat losses respectively through the digester wall above and below ground level (W),

Q_{floor} – is the heat losses through the digester floor (W),

$Q_{air\text{-}out}$ – is the heat losses through the digester cover by the air flow between the membranes of the cover (W).

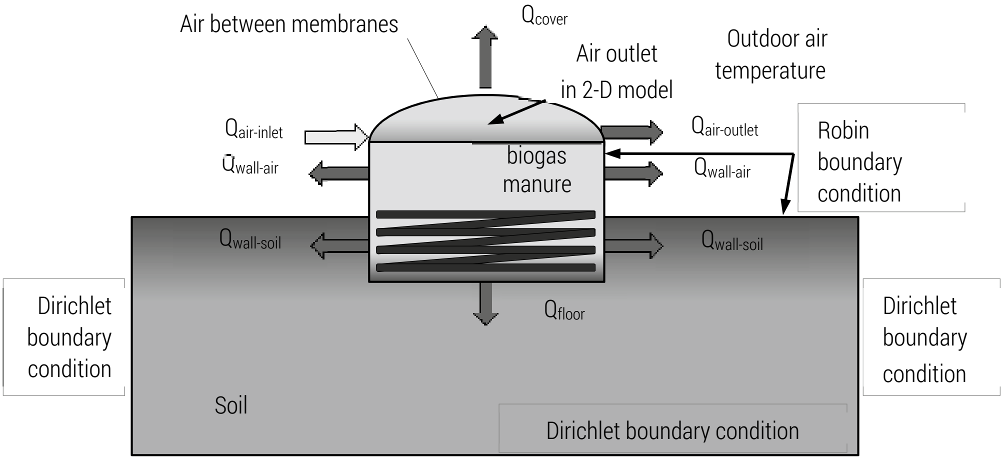

Figure 4. Heat transfer process between anaerobic digester and surrounding with axis of symmetry 2-D axisymmetric steady heat transfer model

Source: author's own work.

Boundary condition

The analysis of 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 (boundary condition, figure 4) for different depth is presented on figure 5 (Rynkowski, 2017). The manure temperature in biogas digester was obtain from biogas plant data (figure 3).

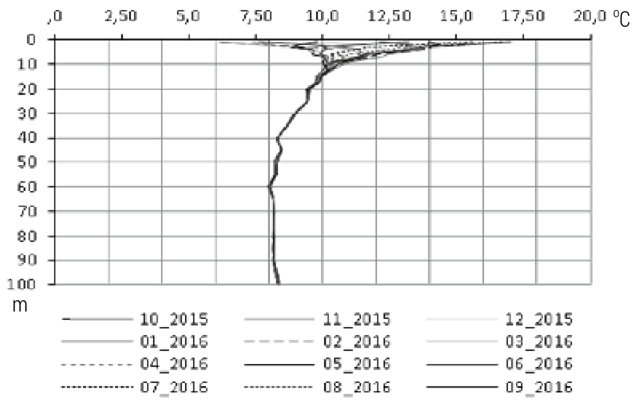

Figure 5. Average undisturbed ground temperature profile

Source: (Rynkowski, 2017).

Between the cover membranes is pumped the outdoor air. According to measurements the velocity of the air is near 4 m/s, diameter of inlet and outlet is 100 mm. Because of 2-D axisymmetric model, it was assumed that the inlet is like in practice, while the outlet is at the central point of upper part the cover (figure 4). Heat loss analysis at different inlet air speeds is considered.

Simulation method

Two-dimensional axisymmetric mesh upper part of model is shown on figure 6. 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.

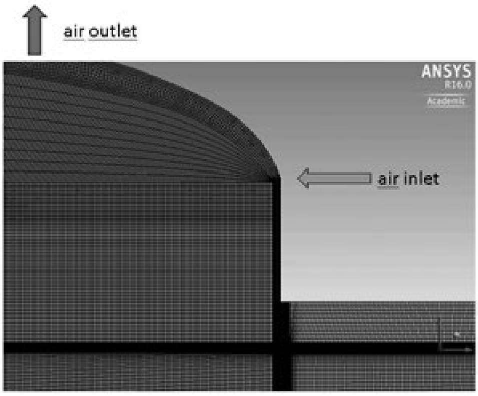

Figure 6. 2-D axisymmetric fragment mesh model with air inlet and outlet points
Source: author's own work.

Table 1. Thermophysical properties of the material

Term	Material	Density kg/m³	Thermal conductivity coefficient W/(m·K)	Specific heat capacity J/(kg·K)
Soil	Loess	1650	1,00	840
Insulation	Styrofoam	40	0,04	1 460
Wall	Reinforced concrete	2 300	2,30	1 000
Cover	Membrane EPDM	900	0,06	840
Floor	Reinforced concrete	2 500	2,30	840
Biogas (CH_4)	Methane	0,6679	0,0332	2 370
Air (between membranes)	Air	from 1,377 (-22oC) to 1,202 (17oC)	0,0242	1 006

Source: author's own work.

Result and discussion

The model was solved using Fluent R16.0 Academic version. As boundary condition was set average monthly temperatures in the considered location in winter season. The sample of the digestate average temperature distribution for January is presented on figure 7.

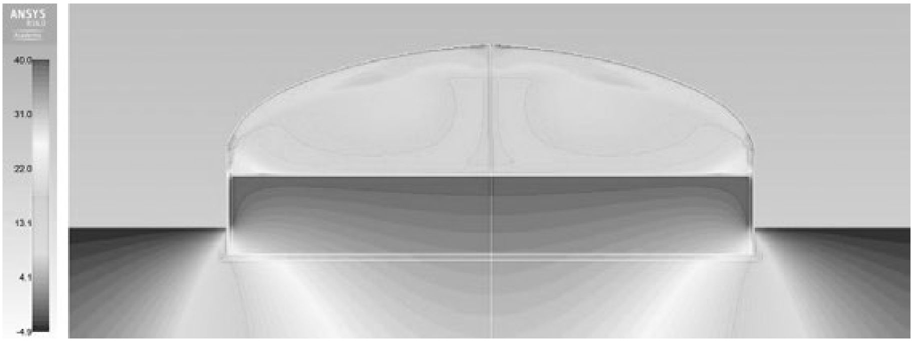

Figure 7. The sample digestate average temperature distribution for January
Source: author's own work.

The monthly average temperatures and heat losses with the average thermal power Q_{HE} of the heat exchanger during the winter season for existing anaerobic digester are presented in table 2. The thermal power of the heat exchanger, taking into account heat demand for manure heating, for heat loss was independently determined.

Table 2. The monthly average temperatures, heat losses to the environment and operating power of the heat exchanger

Month	Monthly temperature [^oC]	Q [kW]	QHE [kW]
Calculation temperature	-22,0	58,9	-
January	-4,9	44,7	44,0
February	-2,0	42,3	40,3
March	1,7	39,4	25,4
November	1.6	39,3	30,7
December	-1.3	41,8	39,4

Source: author's own work.

Despite the numerous approximations and assumptions used, the numerical results are in good agreement with real data and observations of heat exchanger work. In winter, the anaerobic digester temperature remains in a narrow range, between 35,7°C and 39°C (figure 3). Base on table 2 the reason of the temperature drop may be underestimation of the heat exchanger or other reasons related to the operation of the exchanger (pollution of the exchanger causing dropping its efficiency). The manure has a large thermal inertia, so the temperature changes slowly with the time.

The important question is: what is the effect of inlet air flow rate between membranes of the BD cover, on heat loss by the cover of the anaerobic digester? The results of the numerical simulations as the average heat loss in winter months in function of air inlet speed presents figure 8.

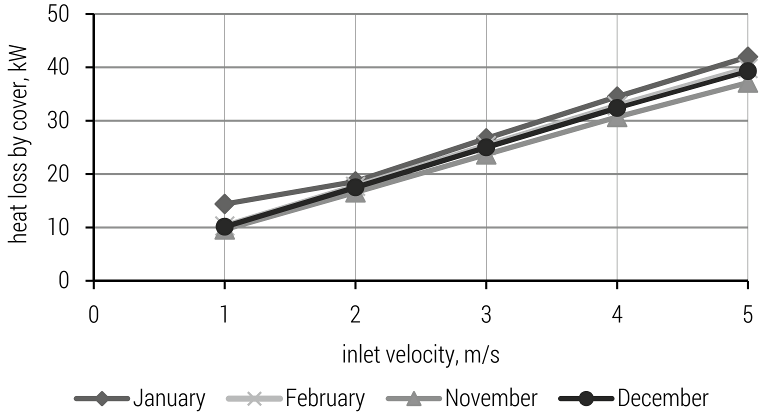

Figure 8. The average heat loss in winter months in function of air inlet speed

Source: author's own work.

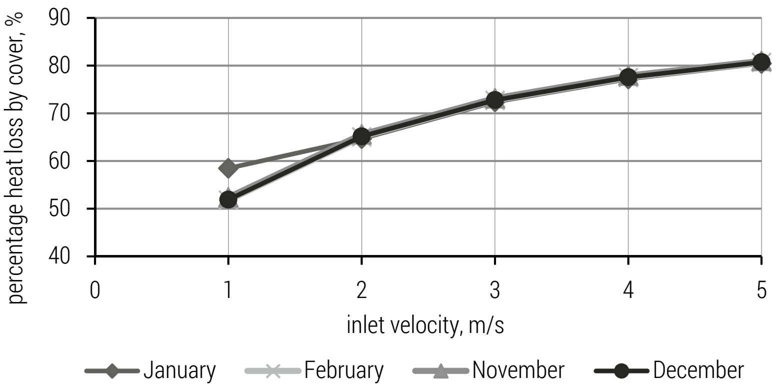

Figure 9. The percentage heat loss in winter months in function of air inlet speed

Source: author's own work.

Conclusion

The results reveal that the heat losses by cover can represent a big part heat loss of the anaerobic digester (figure 8). The heat flux of the cover is the largest, up to four times of the wall. The heat loss of the floor, compering cover, is relatively small, to 1.1 kW for the coldest month, for temperature (-4.9)^{o}C. The numerical experimental results of the heat losses are compared to the heat losses obtained from heat exchanger operating parameters. In each case, for the winter months, the difference between heat losses Q and the operating heat exchanger parameters value Q_{HE} (table 2) are comparatively small. Although, in each case the heat losses are minimal greater than the power of the anaerobic digester the heat exchanger. This can be cause of a local temperature drop of the manure.

Another important question is whether and possibly how the changing of air inlet flow rate between the membranes effect on the heat loss through the dome of digester. The first numerical results show that the influence of that flow is significant. The heat losses by the cover can change in the wide range from about 50% up to near 80% respectively from 1 m/s to 5 m/s in the inlet pipe. These are very large differences that require further analysis. Currently, in real conditions air inlet velocity is about 4 m/s (for 100 mm diameter pipe). For that velocity, the value of the heat loss determined in numerical calculations are similar with real heat loss (table 2).

In engineering problems, a constant value of thermal air resistance is assumed. The air movement is not taken into account at all.

The conclusions from work are:

- the heat loss by the cover in analyzed BD is near 75% of total heat loss (for 4 m/s inlet speed),
- the reason for the manure temperature drop is to low the exchanger's power,
- the heat losses by the cover can change in the wide range from about 50% up to near 80% of total heat loss (from 1 m/s up to 5 m/s in 100 mm inlet pipe).

Further experimental works on this topic are necessary.

Acknowledgements

The study has been implemented from the resources of the S/WBiIŚ/4/14 statutory work financed by the Ministry of Science and Higher Education in Poland.

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