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Assessment of the flow of substrate and agricultural biogas through the adhesive skeleton bed in phenomenological and numerical terms

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Abstract The paper reviews selected methods of agricultural biogas production and characterizes their technical and technological aspects. The conditions of the anaerobic fermentation process in the reactor with adhesive skeleton bed were analyzed. The required technological criteria for the production of biogas from a substrate in the form of pig slurry were indicated. As part of experimental studies, evaluation of the biogas replacement resistance coefficient and the permeability coefficient as a function of the Reynolds number were made. The method of numerical simulation with the use of a tool containing computational fluid dynamics codes was applied. Using the turbulent flow model – the RANS model with the enhanced wall treatment option, a numerical simulation was carried out, allowing for a detailed analysis of hydrodynamic phenomena in the adhesive skeleton bed. The paper presents the experimental and numerical results that allow to understand the fluid flow characteristics for the intensification of agricultural biogas production.

Keywords: Pig slurry; Agricultural biogas; Adhesive bed; Permeability; CFD

Nomenclature

a	–	wave number in the x-direction, m
A	–	surface, m^2
d	–	diameter, m

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K	–	permeability coefficient, m^2
Q	–	volume flow rate, m^3/s
P	–	pressure, Pa
$\Re$	–	Reynolds number
V	–	volume, m^3
w	–	velocity, m/s

Greek symbols

Δ	–	difference (decrease)
η	–	dynamic viscosity coefficient, Pa s
ρ	–	density, kg/m^3
ζ	–	modified coefficient of flow resistances

Subscripts

g	–	gas
z	–	adhesive bed
m	–	measured value
ε	–	apparent

1 Introduction

There are many possibilities of anaerobic digestion [1–6], but the most important is the choice of the fermentation chamber operation mode [7]. Fermentation chambers are the "heart" of the biogas plant, as the actual fermentation process takes place there [8]. A biogas plant can be equipped with one or several fermentation chambers, which depends on the applied technological solutions. The chambers may be concrete or steel, provided with heating installation, they must be properly insulated, allowing access to the interior in the event of a breakdown or the need for maintenance or repair works. The chambers are most often built on the ground surface, less often they are partially recessed. It is also possible to completely recess the chambers in the ground, which allows for better thermal insulation, but hinders access to its interior or auxiliary devices [9]. The configuration of a biogas plant, which takes place already at the planning and design stage, should first of all depend on the characteristics of the available substrates [6].

The installation for the production of biogas is most often integrated with a system that uses the resulting biogas, for example in a cogeneration unit. The basic elements of biogas plants are:

- the system of preliminary preparation and introduction of the substrate,
- fermentation chamber,

- fermented substance storage tank,
- biogas tank,
- cogeneration unit.

The system for the initial preparation of substrates is a tank with equipment that allows grinding substrates, mixing to obtain the proper consistency and dosing, usually by means of pumps, to the fermentation chamber [10, 11].

The current state of knowledge about the operation of agricultural biogas plants concerns relatively large installations with a capacity from 250 kW to 3 MW and relatively simple technologies of using biomass produced mainly on arable land. Numerous scientific reports concern standard tests of anaerobic digestion of substrates and co-substrates constituting production residue and by-products generated on farms and in rural areas. Publications in this field provide knowledge about the biogas production efficiency of individual types of biomass used for biogasification [12]. Much less available publications contain the results of studies on the preparation of specific fermentation mixtures from available substrates and co-substrates with already known biogas-generating capacity. Such research is carried out at the Institute of Technology and Life Sciences – National Research Institute in Falenty, Poznan Branch [13, 14].

2 Experiments

2.1 Scope and research methodology

At the Institute of Technology and Life Sciences, Poznan branch, a pilot installation was developed [15]. The raw biogas production node is a transport system for the biogas produced in the fermentation tank along with the equipment. It enables the fermentation process to be carried out, its control and regulation [16]. The design and construction of a monosubstrate, flow biogas reactor model was carried out on the basis of the invention [17]. The fermentation tank (cylindrical shape) is positioned vertically and the bottom of the tank is frusto-conical with a centrally located drain. The tightness of the fermentation tank is ensured by the lid closing the fermenter with a sealing element. Pilot biogas production (Fig. 1a), which includes the following systems: hydrodynamic mixing, heating, and immobilization [18], with the use of pig slurry, was located on a farm with 1100 porkers kept in a grate system.

(a) (b)

Figure 1: Pilot biogas plant: (a) location of the biogas plant – from the right: a fragment of a piggery building, a monosubstrate flow reactor for meta-new liquid manure fermentation with an installation for the production of agricultural biogas, a lagoon for post-fermentation; (b) an adhesive bed made of vertical pipes with a roughness of 80 μm, transported to the inside of the fermenter.

Inside the fermentation tank there is a filling, i.e. a skeleton bed made of vertical pipes (polyvinyl chloride (PVC) material) constituting the so-called 'basket' (Fig. 1b), the role of which is to increase the active surface for the flora of fermentation bacteria. The filling is at a height of 1.22 m from the bottom of the tank. The basket is based on the supports which at the same time center it in relation to the axis of the system [18].

During the start-up, which lasted 10 days, manual control was used: – heating the circulation liquid of the fermentation chamber, – pumping the substrate into the pre-tank, – pressure regulation in the gas installation, – dosing of additives stabilizing the biogas mass flow rate, – fill level in inlet tank [15, 18]. Automatic control was introduced gradually in the section: – circulation of the fermentation liquid in the fermentation chamber, – dosing the feeding substrate into the fermentation chamber, – evaluation of the level of filling the fermentation chamber, biogas composition and analytical parameters of technological liquids.

The start-up was carried out for 10 days on a digestate liquid inoculum from a biogas plant from the Wielkopolskie Voivodeship (west-central part of Poland) with analytical parameters of the process: temperature 27.2°C, pH 8, dry mass 4.37% dm, dry organic mass 62.25% dm, total inorganic carbon 17.641 mg/dm^3, volatile fatty acids 3.117 mg CH_3COOH/dm^3, alkaline buffer potential 0.177 for a starting volume of 10 m^3. The liquid substrate was slurry of fattening pigs with analytical parameters of the process: temperature 26.5–30.5°C, pH 7.8–8.0, dry mass 3.92% dm, dry organic mass 66.70% dm, total inorganic carbon 19.678 mg/dm^3, volatile fatty acids 8.958 mg CH_3COOH/dm^3, alkaline buffer potential 0.450 for the feeding volume 250–500 dm^3. As a result, the gas pressure in the installation was obtained at the level of 1.5–2.5 kPa and the concentration of biogas components: CH_4 57.3%, CO_2 28.5%, O_2 0.3%, and H_2S 0.000232%.

The research material was made of skeletal bed (72 pipes) with parameters: height $h_z = 2.030$ m; diameter $d_z = 1.620$ m; bed volume $V_z = 0.4564$ m^3; the bed porosity $\varepsilon = 10.91\%$, (≈ 0.11); cross-sectional area $A_z = 0.2266$ m^2. The elementary skeleton bed unit was a pipe (1 item is an apparent elementary bed unit): height $h_r = 2.030$ m; diameter $d_r = 0.16$ m; the volume of the pipe (ring) $V_r = 0.00634$ m^3.

2.2 Research results and their analysis

The experimental research concerned a measuring system for evaluation of the amount of biogas under the conditions of biogas production process. The research was carried out to measure the biogas flow rate resulting from the reference pressure in the fermentor. An independent assessment of the amount of biogas and the pressure drop in the skeletal bed was carried out.

When assessing flow resistance, the analogy to flow through closed channels is the most often used, in accordance with the Darcy and Weisbach equation [19]. On the other hand, the flow resistance is described as a function of the apparent velocity, which is defined as the gas stream related to the surface (cross-sectional area) of the adhesive bed

$$w_\varepsilon = \frac{Q_g}{A_\varepsilon}\,. \tag{1}$$

Whereas the flow resistance coefficient

$$\zeta_\varepsilon = \frac{2}{\rho_g w_\varepsilon^2}\Delta P_m \tag{2}$$

is described as a function of the Reynolds number

$$\mathrm{Re}_\varepsilon = \frac{w_\varepsilon d_\varepsilon \rho_g}{\eta_g}\,. \tag{3}$$

The equivalent diameter was calculated as follows:

$$d_\varepsilon = \frac{V_z}{A_z}\,. \tag{4}$$

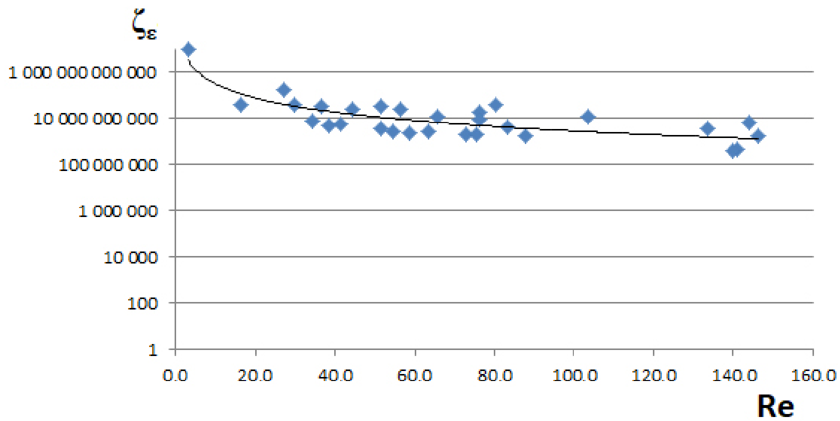
When interpreting Fig. 2a, it should be indicated that there is a non-linear tendency characteristic for the dominance of turbulent flow – it is related to the deviation from Darcy's law [19]. The system of pipes located vertically – constituting the adhesive bed – has a decisive influence on the domination of turbulent flow. Attention should also be paid to the roughness of the pipe surface, thanks to which there is also an intensive production of biogas due to the deposition of microorganisms on the surface of the skeletal bed elements (a foaming layer is produced). In this way, the reproducing microorganisms feed on cyclically fresh substrate, producing biogas under conditions of intensive use in the fermenter.

Taking into account the volumetric flow rate, the permeability of the porous bed can be determined by experiment if the properties of the fluid and the geometric parameters of the flow system are known. The pressure drop across the bed is an experimental value. If the hydrodynamic parameters (flow rate, pressure drop, material porosity, and gas type) are known, the value of the permeability coefficient can be written as

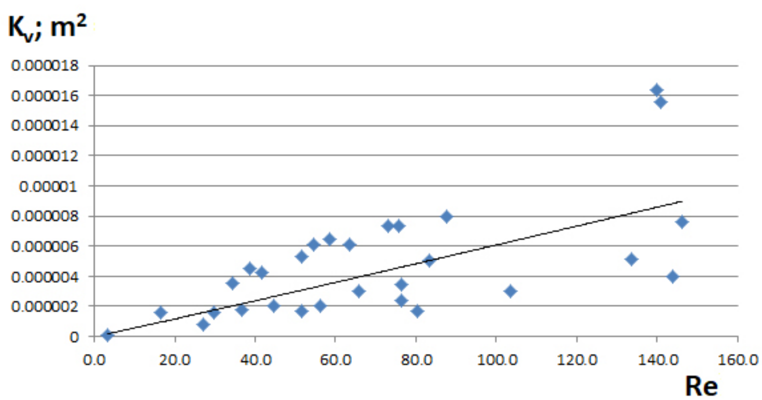
$$K_V = \frac{Q_g}{\sqrt{\dfrac{\Delta P_m}{\rho_g}}}\,. \tag{5}$$

The basis for assessing the hydrodynamics of gas flow through the adhesive bed is the gas permeability characteristic, Fig. 2b, which results from the pressure that forces this flow. In each case, the determination of this characteristic consists in determining the influence of the biogas stream on the value of this overpressure, equivalent to the pressure drop – it is tantamount to determining the total biogas flow resistance through the adhesive bed.

When interpreting Fig. 2b, it should be noted that with the increase of the Reynolds number, the permeability of the adhesive bed increases. The mechanism of biogas flow through the adhesive bed, in analogy to gas permeability for the structural model of a porous material, allows to recognize the problem of gas permeability by pointing to hydrodynamic aspects. This translates into ferment retention, which has so far been a determinant of the quality of biogas production – that is, ferment (it reacted for several days until the substrate was gassed). Taking into account the dependence of the gas permeability coefficient, it should be stated that the quality of biogas, regardless of retention, is significantly influenced by the flow stream and the criterion number in the form of the Reynolds number.



(a)



(b)

Figure 2: Distribution of experimental points: (a) influence of the Reynolds number (Re) on the descending coefficient of biogas flow resistance for the adhesive bed (ζ_ε); (b) the effect of the Reynolds number (Re) on the gas permeability coefficient (K_V) of the adhesive bed.

3 Numerical simulation of hydrodynamic phenomena in the adhesive skeleton

The geometry of the object was created in the Space Claim Direct Modeller [20] program on the basis of the fermenter working documentation. The geometry includes the substrate inlet and outlet pipe (slurry), a bundle of pipes, and bubble tubes. The numerical grid was created in the Ansys

Meshing program [20]. Due to the size of the model, the boundary layer was not generated, which may affect the accuracy of the results. A hexagonal mesh was generated in most volumes. To achieve this, the geometry was decomposed into smaller – simpler solids.

The flow model has been defined in the commercial fluid simulation software Ansys Fluent [20]. Basic information about the flow model is presented below: a) turbulent flow – Reynolds-averaged Navier–Stokes (RANS) model with the enhanced wall treatment option; b) two-phase flow in the volume of fluid (VOF) approach in the explicit wording; c) SIMPLE (semi-implicit method for pressure linked equation) calculation algorithm; d) second order of discretization of the momentum equation; e) geo-reconstruct interphase boundary tracking algorithm; f) running track controlled by means of residual observations.

Fluid parameters:

a) pig slurry: density 998.2 kg/m^3, viscosity 0.0015 Pa·s (50% higher than that of water);
b) gas modeled as air: density 1.225 kg/m^3, viscosity 0.0000017894 Pa·s;
c) external forces: gravity 9.81 m/s^2.

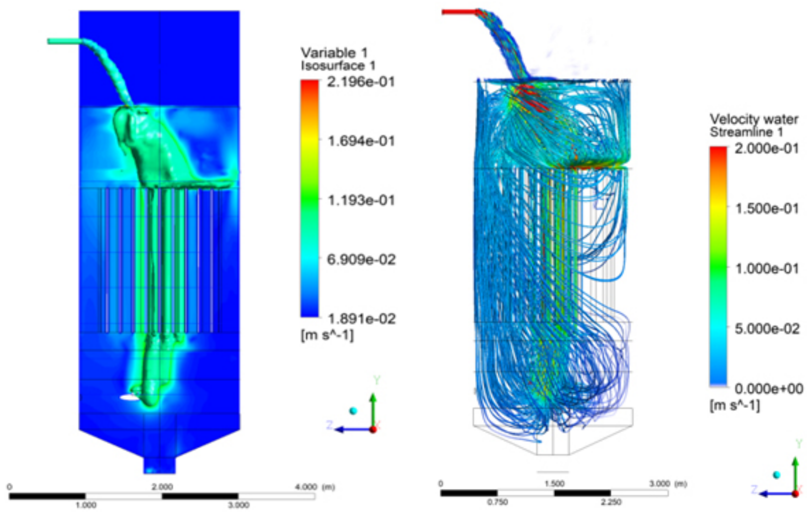
Boundary conditions:

a) slurry inlet: 7.209222 kg/s;
b) inlet turbulence intensity: 5%;
c) inlet turbulent viscosity ratio: 10.

The obtained results were analyzed and the following visualizations were created. The area of penetration of the stream of slurry introduced into the fermentor is shown in Fig. 3a. It can be seen that the main flow occurs in a few selected tubes constituting the adhesive bed. The stream lines are shown in Fig. 3b, mixing can be observed in most of the column volume except in the area at the bottom of the column opposite the inlet pipe. A recirculation zone was also observed which may indicate very limited agitation in this part of the fermentor. It should be noted that the flow through the few tubes of the adhesive bed is from top to bottom, and for most tubes the flow is from bottom to top.

The analysis of the obtained results shows the limitations of the simulation. The simulations performed are characterized by the following limitations affecting their accuracy (ordered from the most significant):

- Slurry is modeled as a liquid of constant viscosity. Literature data show that the slurry viscosity strongly depends on its composition and that it exhibits strong properties of a non-Newtonian fluid.



(a) (b)

Figure 3: Numerical evaluation of the flow in the fermentor: a) velocity isosurface – quality view of the main mixing area and where the highest velocities occur; b) streamlines – view of the recirculation zone.

- The viscosity depends on the tangential stresses. When modeling the tube bundle, small spaces between the tubes were ignored.
- The generated mesh does not have a boundary layer.

The slurry has the greatest impact on the modeling accuracy, while the developed results provide qualitative information on the course of hydrodynamic mixing in the skeletal fermenter.

4 Summary

The popularization of agricultural biogas plants still requires research on the determination of basic indicators determining the energy consumption of individual techniques, their comparison and selection in terms of pro-ecological, economic and energy expenditure. Frequent changes in the production system with the participation of methanogenic factors, forced by modern practice, require continuous experimental research.

In the context of the criterion number for hydrodynamic conditions, the problem of the flow of biogas through the adhesive bed was described. The paper presents results of experimental studies which indicate a clear influence of flow resistance in relation to the Reynolds number. It was found that the biogas production using an adhesive bed is determined by the characteristic parameters: the degree of porosity for the gas flow and the Reynolds number, which, with an increase, causes a decrease in the descending biogas flow resistance coefficient. Taking into account the indicated parameters, a model and methodology were developed and applied to determine the permeability coefficient.

Using a numerical tool in the form of computational fluid dynamics, the occurring hydrodynamic phenomenon in the adhesive skeleton bed located in the biogas fermenter was indicated.

The mixing system used in the fermenter according to the invention ensures homogenization of the composition of the fermentation mass, as well as providing ingredients qualitatively supporting the fermentation process. This improves the process of converting liquid slurry to biogas, ensuring simple and reliable biogas production. The rough surfaces of the pipes contribute to a better foundation of the flora of fermentation bacteria.

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References

[1] Grzegorzewicz J., Gruszecki Z., Ścieżyński H., Cieślak R., Smaga M., Jurkowski A., Matyja K., Papuga W.: Bubble Reactor. Patent Office of the Republic of Poland. Patent Application P.174663, 1994 (in Polish).

[2] http://pfee.de/en/cellroll/ (accessed 15 Apr. 2018).

[3] http://www.ows.be/household_waste/dranco/ (accessed 15 Apr. 2018).

[4] https://www.hz-inova.com/hitachi-zosen-inova-doubles-up-with-contract-for-second-kompogas-plant-in-peloponnese-region/ (accessed 12 May 2018).

[5] http://www.valorgainternational.fr/en/mpg3-128079–VALORGA-S-ANAEROBIC-DIGESTION-PROCESS.html (accessed 12 May 2018).

[6] Oniszk-Popławska A., Matyka M.: *Final report on the field research. "Comprehensive assessment of the conditions for biogas production in the Lubelskie Voivodeship"*. Regional Economic Change Management System, 2012 (in Polish).

[7] Jedrczak A.: *Biological waste treatment*. Przegląd Komunalny (2001), 6, 89–92 (in Polish).

[8] Wałowski G.: *Developing technique anaerobic digestion in the contex of renewable energy sources*. In: Proc. 26th Eur. Biomass Conf., Copenhagen, 14-17 May 2018, 798–808

[9] Kowalczyk-Juśko A.: *Biogas plants an opportunity for agriculture and the environment*. Fundacja na rzecz Rozwoju Polskiego Rolnictwa, 2013 (in Polish).

[10] Głodek E.: Report on the EU project POKL.08.02.01-16-028 / 09 Sources of Energy in the Opole region 2013 promotion, technologies, support, implementation. Institute of Ceramics and Building Materials, Opole 2010. (in Polish).

[11] den Boer E., Szpadt R.: *Biogas plants as an opportunity for agriculture and the environment]*. In: Proc. Conf. on 24 Oct. 2013, Dolnoślaski Ośrodek Doradztwa Rolniczego we Wrocławiu (in Polish).

[12] Karłowski J., Kliber A., Myczko A., Golimowska R., Myczko R.: *Agronomy in the sustainable development of modern agriculture]*. In: Proc. 4th Sci. Conf. of the Polish Agronomic Society, Warszawa, 5-7 Sept. 2011 (in Polish).

[13] Myczko A., Myczko R., Kołodziejczyk T., Golimowska R., Lenarczyk J., Janas Z., Kliber A., Karłowski J., Dolska M.: *Construction and Operation of Agricultural Biogas Plants*. Wyd. ITP, Warszawa Poznań 2011.

[14] Kołodziejczyk T., Myczko R., Myczko A.: *Use of residual non-food cellulosic material for biogas production*. Ciepłownictwo, Ogrzewanictwo, Wentylacja **42**(2011), 9, 360–363. (in Polish).

[15] Wałowski G.: *Interpretation of the mechanism of biogas flow through an adhesive bed in analogy to gas-permeability for a structural model of a porous material*. Int. J. Curr. Res. **10**(2018), 12, 76225–76228.

[16] Wałowski G.: *Multi-phase flow assessment for the fermentation process in monosubstrate reactor with skeleton bed*. J. Water Land Dev. **42**(2019), 7-9, 150–156.

[17] Myczko A., Kliber A., Tupalski L.: *The latest achievements in the field of renewable energy sources along with the presentation of barriers to the implementation of research results into business practice*. In: The Latest Developments in the Field of RES, Including the Presentation of Barriers to the Implementation of Research Results in Business Practice and Suggestions for their Solutions (B. Mickiewicz, Ed.), Koszalin 2012 (in Polish).

[18] Wałowski G., Borek, K. Romaniuk W., Wardal W.J., Borusewicz A.: *Modern Systems of Obtaining Energy – Biogas*. Wydawnictwo Wyższej Szkoły Agrobiznesu w Łomży, Łomża 2019 (in Polish).

[19] Strzelecki T., Kostecki S., Żak S.: *Modelling of flows through porous media*. Dolnoślaskie Wydawnictwo Edukacyjne, Wrocław, 2008. (in Polish).

[20] https://www.ansys.com/products/fluids/ansys-fluent (accessed 15 Apr. 2018).