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RESEARCH ARTICLE

INTERPRETATION OF THE MECHANISM OF BIOGAS FLOW THROUGH AN ADHESIVE BED IN ANALOGY TO GAS-PERMEABILITY FOR A STRUCTURAL MODEL OF A POROUS MATERIAL

[1,2]*Grzegorz Wałowski

[1]Institute of Technology and Life Sciences in Falenty, Al. Hrabska 3, 05-090 Warsaw, Poland
[2]Department of Renewable Energy Resources, 67 Biskupińska Street, 60-463 Poznań, Poland

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ABSTRACT

The issue of the mechanism of biogas flow through the adhesive bed was described and flow analogy was made for the porous structure model. With regard to the problem of biogas flow through the adhesive bed, the process issue was recognized in the description of the mechanism of gas movement in the porous structure for the development of a new generation of alternative energy sources, especially biogas production from swine slurry. The paper presents preliminary results of experimental tests in the field of hydrodynamics evaluation of biogas flow through an adhesive bed. The gas flow resulting from overpressure forcing this flow was assumed as the basis for the assessment of hydrodynamics of biogas flow. The measurement results indicate a clear influence of the flow resistance in relation to the gas permeability coefficient of the bed.

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INTRODUCTION

As for the hydrodynamic approach, the mechanism of gas flow in porous deposits is strictly connected with a geometrical structure of the porous medium and is subject to dimensions (diameter), shapes and tortuosity of the channels. We can distinguish here the basic case of fluid flow in porous beds, as illustrated in Fig. 1 (Szmigielski, 2006). The flow only occurs inside the pores and the channels that determine the porosity of the frame structure. Since this structure may have closed pores (and frequently blind pores), the flow through such material is only observed in the interconnected open channels. An additional complexity of hydrodynamics is based on the fact that those structures comprise compact (rigid) deposits and cannot be loosened in any way when an increase in pressure in the structure is observed. As for gap-porous deposits e.g. shale formations (shale gas) the authors of those studies (Burdine, 1953; Gonet *et al.*, 2010; Mualem, 1992; Szott and Gołąbek, 2012) conclude that the gas flow conditions are significantly affected by the deposit porosity system resulting from the shape of channels and capillaries. The model solutions formulated by those authors relate to the shape of interconnections between capillaries and are based on the following assumptions:

- Models of uniformly-shaped circular and symmetrical capillaries:
- Burdine's model (Burdine, 1953) – cylindrical capillary with a constant radius Fig. 2.

In most cases, the first group of models is characterised by the simplest geometry of pores, i.e. cylindrically-shaped flow channels according to Burdine's model (Burdine, 1953). A base element of this model only comprises a cylindrical capillary with a constant radius, it may successfully be used in process calculations of the heat and mass exchange (Grunewald and Bomberg, 2002; Grunewald *et al.* 2002;Mid-Term, 1999). An extension of the group of uniformly-shaped circular and symmetrical capillaries is structural (double) models in which the liquid flows through the symmetrical porous matrix comprising a set of circular and symmetrical capillaries Fig. 3 with an identical radius and length (as Burdin's model).

MATERIALS AND METHODS

Experiments: In Institute of Technology and Life Sciences, Department of Renewable Energy Sources, Poznan Branch has developed system of installations with a power of (3÷40) kW. It is a pilot installation Fig. 4 with an active capacity of 15 m^3 of fermenter was located in a farm with 1100 fatteners (pigs) kept in a grate system.

****Corresponding author:*** **Grzegorz Wałowski,**
1Institute of Technology and Life Sciences in Falenty, Al. Hrabska 3, 05-090 Warsaw, Poland.
2Department of Renewable Energy Resources, 67 Biskupińska Street, 60-463 Poznań, Poland.

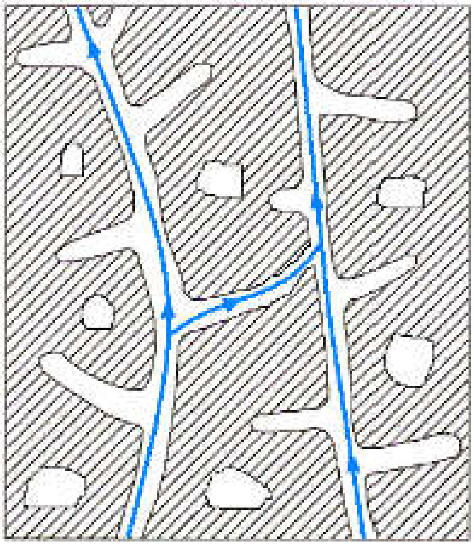

Fig. 1. Diagram of liquid flow through a porous deposit rigid frame-structured channel with open flow channels and blind and closed pores (Szmigielski, 2006)

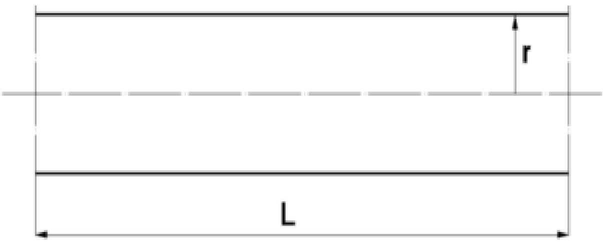

Fig. 2. Burdine's cylindrical capillary model (Burdine, 1953): L - length, r – radius

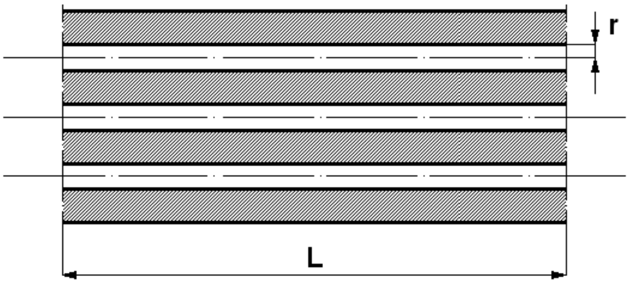

Fig. 3. Structural model of the porous capillary body (Aksielrud & Altszuler, 1987): L - długość, r – promień

Fig. 4. Pilot installation - examples of techniques of the anaerobic fermentation of waste - mono-substrate reactor

Fig. 5. Adhesive bed - the filling is a "basket" with pipes type A PVC-U S4 UD - roughness after sanding is 80 µm

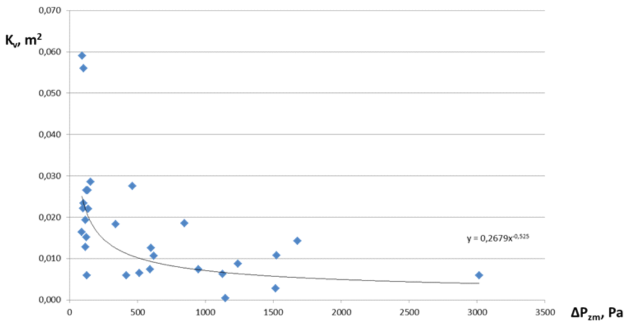

Fig. 6. Effect of flow resistance ΔP_{zm} on the gas permeability coefficient K_V of the adhesive bed - - distribution of experimental points.

The raw biogas production unit is a biogas transport system produced in the fermentation tank with its equipment and enables the fermentation process to be carried out, controlled and adjusted. The fermentation tank Fig. 4 is the main and key component of the system for achieving the maximum efficiency of the fermentation technology. The raw biogas production system consists of the following unit elements. The digestion tank is designed for a system in a vertical position. The bottom of the tank is truncated cone shaped with a centrally located trigger. The fermentation tank is sealed by a lid that closes the fermenter with a sealing element. The raw biogas production unit consists of the following elements:

Circulation system - description of the system operation. The fermentation tank is filled with biomass from the top to ensure directional migration of the fraction through the entire system. The biomass vertical circulation system and the freshly extracted biogas circulation system are used for mixing the fermentation tank content. The biomass mixing system ensures the homogenization of the composition and temperature of the ferment as well as delivery of certain ingredients supporting the fermentation process. Mixing the content of the fermenter for averaging its composition is performed by means of a barbotage. This is done in such a way that part of the biogas is extracted from the fermenter gas compartment by means of a blower and fed through a non-return valve into the lower part of the bioreactor via a bubbler system. Gas flows out of the bubblers in the form of bubbles and mixes the suspension upwards. Immobilization system - description of the system operation. Inside the fermentation tank there is a fill, i.e. a skeletal deposit made of vertical pipes PVC constituting the so-called "basket", whose purpose is to increase the active surface area for the flora of fermenting bacteria. The filling is located at a height of 1.22 m from the bottom of the tank, the so-called "basket" - Fig. 5 is supported by supports, which also centralize it in relation to the axis of the system. Heating system - description of the system operation. The inner wall of the fermentation tank is equipped with a heating spiral in the form of a plastic pipe DN32. The heating medium is hot water taken from the main heat exchanger located near the co-generator. For optimal biogas conditions, the walls, conical bottom and fermenter cover are insulated to limit heat emission to the outside. The optimal working conditions of the fermenter are as follows temperature (35÷40)°C, gas hypertension (10÷20) kPa. Currently, intensive work is underway to test the software for controlling the installation. After the acceptance of the installation, the start-up phase on pig slurry occurred.

After the acceptance of the installation, the start-up phase on pig slurry occurred. The start-up was carried out for 10 days on a digestate liquid inoculum from a biogas plant from the Wielkopolskie voivodship with analytical parameters of the process (Report, 2018): temperature 27.2^{0}C, pH 8, dry mass 4.37% dm, dry organic mass 62.25% dm, OWN 17.641 mg / l, LKT 3.117 mg CH_3COOH/l, APB 0.177 for a starting volume of 10m^3. The liquid substrate was slurry of fattening pigs with analytical parameters of the process: temperature (26.5-30.5) ^{0}C, pH (7.8-8.0), dry weight 3.92% dm, dry organic mass 66.70% dm, OWN 19.678 mg / l, LKT 8.958 mg CH_3COOH/l , APB 0.450 for the feeding volume (250-500) liters. As a result, the gas pressure in the installation was obtained (15-25) mbar and the concentration of biogas components: CH_4 57.3%, CO_2 28.5%, O_2 0.3%, H_2S 232 ppm.

Scope and research methodology: In order to understand the hydrodynamic conditions of the gas flow through the adhesive material, experimental investigations have been carried out to assess the gas-permeability of the skeletal structure material. The research material was made of skeletal bed (72 pipes - Fig. 5) with parameters: height h_z = 2030 mm; diameter d_z = 1620 mm; bed volume V_z = 0.4564 m^3; the bed porosity ε = 10.91%, $\varepsilon \approx 0.11$; 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 = 2030 mm; diameter d_r = 160 mm; the volume of the pipe (ring) V_r = 0.00634 m^3. Experimental research was related to the measurement system for assessing the gas-permeability of the adhesive bed under the conditions of the biogas production process. The research was carried out in the field of biogas flow rate measurement resulting from the reference pressure in the fermenter. Independent assessment of the gas permeability and pressure drop on the adhesive bed was performed.

RESULTS AND DISCUSSION

The basis for a detailed analysis of fluid flow in porous media is still Darcy law. In its original form, this law describes the conditions for permeability of various kinds of grained bed by reference to the filtration mechanism during laminar flow of water through a sand layer, which constitutes a model grained medium. If the variability of liquid properties is take into account the, the velocity through a porous bed will be proportional to the change in density ρ and inversely proportional to the change in viscosity η (Strzelecki *et al.,* 2008). Then the Darcy equation describing the permeability Q of the porous bed takes the following formula (1):

$$Q = K A_o \frac{\rho \hat{g}}{\eta} \frac{\Delta h}{L} \tag{1}$$

where K - coefficient of vertical permeability, m^2; A_o - layer bed cross-section, m^2; ρ – density, kg/m^3; g –earth acceleration, *m/s^2; Δh* - denotes pressure drop, Pa; η – viscosity, Pas; L - height of porous medium, m. This formula remains one of the characteristics of the contemporary description of this phenomenon, although it refers only to laminar flow. The K coefficient in equation (1) describes the so-called permeability of a porous medium, and its value, as shown by the Darcy model, is characteristic of a given porous medium. Since this coefficient (by definition) has a surface dimension, its value from a hydrodynamic point of view – as characteristic dimension – is very often considered as a certain geometric feature that characterizes the total permeability of the porous material. On the other hand, the value of such permeability depends not only on filtration characteristics of the porous medium (its structure, particle size, their density, porosity etc.), but also on the physical properties of fluid, especially its viscosity (Waluk, 1973). As a rule, this factor does not depend on the shape and size of the bed itself. Of course, the Darcy model also applies to the description of pressure flows. Then for equation (1) we will get (2):

$$Q = K A_o \frac{\Delta P}{\eta L} => K = \eta \frac{Q}{A_o} \frac{L}{\Delta P} \tag{2}$$

The last equation shows that for a given volumetric flow rate Q the permeability of a porous bed could be determined by means of experiments if the fluid properties η and the geometrical parameters of the flow system A_o are known. The pressure drop ΔP on the bed is then experimental value.

If the hydrodynamic parameters are known (flow rate, pressure drop, material porosity and type of gas of course), the permeability coefficient value may be determined by means of experiments. Then relationship (3) can be written as:

$$K_V = \frac{Q_g}{\sqrt{\frac{\Delta P_{zm}}{\rho_g}}} \tag{3}$$

where K - coefficient of permeability (own model), m^2; Q - volumetric flow rate, m^3; ΔP - pressure drop, Pa; ρ – density, kg/m^3. The basis for the assessment of hydrodynamics of gas flow through the adhesive bed is the gas permeability characteristics (Fig. 6), which results from the pressure forcing this flow. In each case, the determination of this characteristic consists in determining the impact of the biogas stream on the value of this overpressure, equivalent to a pressure drop - this is tantamount to determining the total resistance of biogas flow through the adhesive bed. Interpreting Fig. 6, it should be noted that there is a non-linear tendency characteristic of the dominance of turbulent flow - this is related to the derogation from Darcy's law (Strzelecki *et al.*, 2008).

Conclusion

The interpretation of the mechanism of biogas flow through the adhesive bed in analogy to gas-permeability for the structural model of the porous material allowed to recognize the problem of gas permeability. The issue of the mechanism of biogas flow through an adhesive bed is described. An experimental investigation into the gas permeability of the material was made and the hydrodynamic phenomenon resulting from the drop in gas flow pressure was evaluated. The paper presents preliminary results of experimental tests, which indicate a clear influence of flow resistance in relation to the gas permeability coefficient of the deposit. It was found that the scale of skeletal permeability of the material is determined by characteristic parameters such as the degree of porosity for the gas flow and the gas permeability coefficient.

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