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STUDY OF THE PROCESS OF HYDRAULIC MIXING IN ANAEROBIC DIGESTER OF BIOGAS PLANT

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Two systems of hydraulic mixing in a vertical cylindrical anaerobic digester: standard and modernised are discussed in the paper. Numerical investigations that were carried out are focused on a study of hydrodynamic processes in an aerobic digester using two various systems of hydraulic mixing as well as on analysis of the efficiency of methane fermentation process accomplished under different geometric parameters of an anaerobic digester and systems of hydraulic mixing.

Keywords: biogas, mixing, hydrodynamics, CFD modelling

1. INTRODUCTION

Mixing of an organic substrate is a key factor that increases the anaerobic digestion process efficiency allowing intensification of the biogas yield by 50%. Results of experimental studies of industrial apparatuses of methane fermentation showed that insufficient mixing reduces the effective volume of the anaerobic digester by 70% and is a major cause of the equipment failure (Giunter and Goldfarb, 1991). Although the mixing process in anaerobic digesters is of great significance because of its direct impact on biogas output, specific effects of the selected mixing mode on biogas production are not clear (Sindall, 2013).

A number of experimental studies were carried out to evaluate the mixing effect on performance of anaerobic digesters revealing that the true mixing effect cannot fully be detected on laboratory scales (Karim et al., 2005). Carrying out full-scale experiments is excessively expensive and often impossible. Besides, with their help it is impossible to find the values of the major characteristics of the process (such as speed, temperature, concentration) throughout the solution region. In contrast to the experiment practically the entire region of the apparatus under study is available for computations and also there are no process disturbances introduced by sensors. Therefore, at present, a numerical experiment is widely applied along with experimental studies of the processes occurring in the anaerobic digester.

Many papers are devoted to the numerical modelling of hydrodynamics and heat and mass transfer processes when mixing in an anaerobic digester of a biogas plant. Maier et al. (2010) studied laminar, transitional and turbulent regimes using the Euler-Euler method. Mândrea et al. (2011) obtained an analytical solution for laminar flow in a cylindrical anaerobic digester with mechanical mixing and a

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numerical solution for laminar flow in an anaerobic digester with more complicated geometry. Kamarad et al. (2013) investigated the mechanical mixing in two full-scale industrial anaerobic digesters and compared the function of residence time distribution of flow particles in the apparatus obtained on the basis of experimental data with results of numerical calculations.

Vesvikar and Al-Dahan (2005) conducted numerical and experimental studies to determine the hydrodynamic flow pattern inside an anaerobic digester with bubbling mixing. For the first time CFD results were estimated using experimental data obtained by Computer-Automated Radioactive Particle Tracking (CARPT). Latha et al. (2009) developed a 3D model of hydrodynamics process for the turbulent flow regime of a non-Newtonian fluid in an anaerobic digester with bubbling mixing.

In order to optimise the anaerobic process several authors developed mathematical models for anaerobic digesters with hydraulic mixing. Terashima et al. (2009) evaluated the field of velocities and concentrations for an organic substrate with non-Newtonian properties in an anaerobic digester with an internal circulation tube. Mendoza et al. (2011) obtained numerical results of the distribution of velocity fields in a cylindrical anaerobic digester with jet mixing. Chmielewski et al. (2011, 2012, 2013) presented the results of numerical studies of hydraulic mixing in a horizontal anaerobic digester with a top feeding of organic raw material as well as the data of laboratory tests and operation of the pilot biogas plant (Berbec et al., 2012; Chmielewski et al., 2012; 2013; Palige et al., 2011). The distinguishing feature of the work of Huang et al. (2014) on study of the process of hydraulic mixing is to model the substrate at the initial stage of fermentation as a fluid with water properties and as a fluid with high concentration and pseudoplastic properties (Euler-Euler method for multiphase fluid) after the fermentation process is over.

The application of a system of hydraulic mixing allows us to maintain the most favourable hydrodynamic and temperature conditions for vital activity of methanogenic bacterial community throughout the entire manufacturing process.

The conducted analytical review indicated that mixing methods have been considerably well studied from the hydrodynamics perspective but there are few results on the spatial distribution in the apparatus that directly influence the amount of produced biogas. In computational methods simplified axisymmetric mathematical models prevail, describing hydrodynamics and heat transfer processes limited by the definition of mean flow properties which does not give an idea of spatial structure of the real flow.

In this paper numerical investigations of two systems of hydraulic mixing in anaerobic digesters are carried out. On the basis of the developed criterion a comparative analysis of the mixing quality using standard and modernised mixing systems is performed.

2. DESIGN OF THE DIGESTER

The paper discusses two systems of hydraulic mixing in a vertical cylindrical anaerobic digester: standard and modernized. Pig manure with solids content of 6% is used as the substrate. The fermentation mode is thermophile. Hydraulic retention time is 12 days.

A standard system of hydraulic mixing is shown in Fig. 1a. Recirculation of the organic substrate is carried out using external circulation loop which consists of a round tube with an impeller pump the organic substrate is supplied through the side wall into the near-bottom region of the apparatus and is discharged from its upper part (Meroney and Colorado, 2009).

A modernised system of hydraulic mixing is presented in Fig. 1b. The fundamental difference between them is the second supply tube located in the center of the upper base of apparatus (Karaeva et al., 2012).

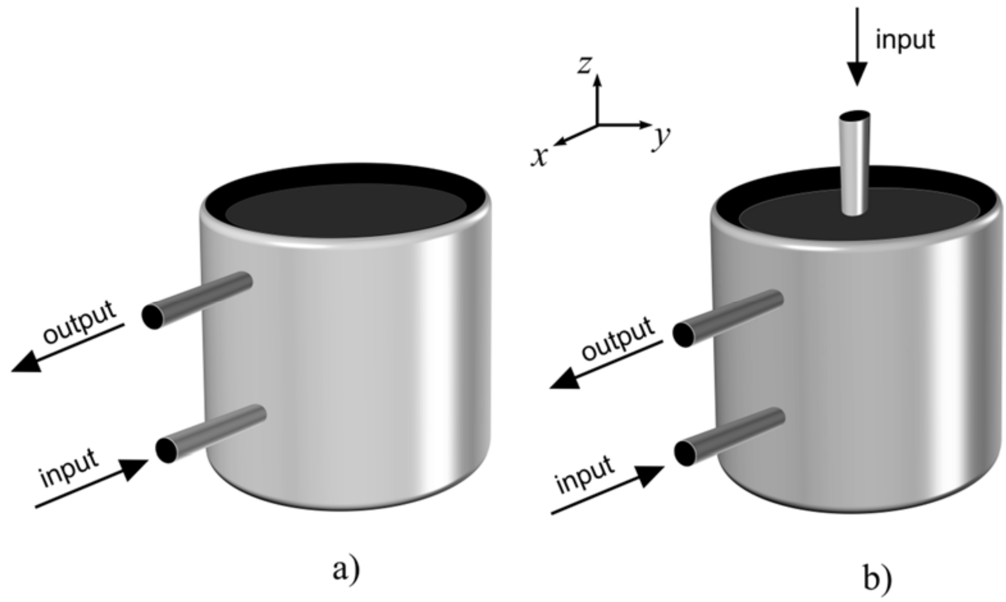

Fig. 1. Schematic representation of the working area of anaerobic digester with a system of hydraulic mixing: (a) standard; (b) modernised

The sizes of anaerobic digesters under study are as follows: diameter D = 1.6 m and height H = 1.6 m; diameter of circulation tubes d_p = 0.1 m; distance from the apparatus bottom to the center of the bottom discharge tube h_1 = 1.5 m; distance from the apparatus bottom to the center of the upper supply tube h_2 = 0.1 m. Numerical studies were performed for the cylindrical anaerobic digesters with a volume of 3 m^3 and the same power consumed for pumping the organic substrate.

3. APPLIED CFD METHODOLOGY

The following assumptions are made when constructing a mathematical model: hydrodynamic regime of substrate circulation in the anaerobic digester is turbulent with a given velocity vector profile at the reservoir input; the considered medium (organic substrate) is a viscous fluid with density and coefficient of effective viscosity depending on concentration and temperature; rheological behaviour of the medium is Newtonian; mixing is non-stationary; mean concentration during the mixing process is constant; temperature in the anaerobic digester is constant. The standard two-parameter turbulence model $k-\varepsilon$ was chosen to describe the turbulent flow of substrate in the anaerobic digester.

The mathematical model has the form:

$$\rho(\alpha)\left(\frac{\partial \overline{V}}{\partial t} + \nabla \overline{V} \cdot \overline{V}\right) = \nabla \cdot \mathbf{T} + \overline{g}\rho(\alpha) \tag{1}$$

$$\frac{\partial \rho(\alpha)}{\partial t} + \nabla \cdot \left(\rho(\alpha)\overline{V}\right) = 0 \tag{2}$$

$$\rho(\alpha)\left(\frac{\partial k}{\partial t} + \nabla k \cdot \overline{V}\right) = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + \mu_T P\left(\overline{V}\right) - \rho(\alpha)\varepsilon \tag{3}$$

$$\rho(\alpha)\left(\frac{\partial \varepsilon}{\partial t}+\nabla\varepsilon\cdot\overline{V}\right)=\nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]+\frac{C_{\varepsilon 1}\varepsilon\mu_T P(\overline{V})}{k}-\frac{C_{\varepsilon 2}\rho(\alpha)\varepsilon^2}{k} \tag{4}$$

$$\frac{\partial \alpha}{\partial t}+\overline{V}\cdot\nabla\alpha=0 \tag{5}$$

$$P(\overline{V})=\nabla\overline{V}:\left(\nabla\overline{V}+\left(\nabla\overline{V}\right)^T\right) \tag{6}$$

The equation of medium state is given by $\mathbf{T}=-p\mathbf{I}+2\mu_e(\alpha)\mathbf{D}$; viscosity of the organic substrate $\mu_e = \mu + \mu_T$, $\mu_T = C_\mu\, \rho(\alpha)\, k^2\, \varepsilon^{-1}$. Empirical constants in the turbulent model $k-\varepsilon$: $C_\mu = 0.09$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$; mixture density $\rho(\alpha)$ is determined by the phase density $\rho(\alpha) = (1-\alpha)\rho_1+\alpha\rho_2$.

The initial distribution of volume concentration for $t = 0$ can be written as the following function:

$$\alpha_0=\alpha_{\max}\frac{\pi/2-arctg\left(b(z-h_0)\right)}{\pi/2+arctg\left(bh_0\right)} \tag{7}$$

Boundary conditions for concentration: at the input ports α = const; at the solid and open boundaries of the reservoir $\frac{\partial\alpha}{\partial n}=0$; at the output stabilisation of concentration fields $\frac{\partial\alpha}{\partial n_1}=0$. Initial hydrodynamic conditions: $\overline{V}_0=0$. Boundary conditions for velocity: no-slip conditions of the fluid $\overline{V}=0$ are specified at the solid boundaries of the reservoir; velocity profiles corresponding to the formed velocity profile of Newtonian fluid in the round tube are specified at the input ports; at the open boundary $(p_g-p)\overline{n}+2\mu\mathbf{D}\overline{n}=0$; at the output – a condition of stabilization of velocity $\frac{\partial\overline{V}}{\partial n_1}=0$.

Numerical implementation of the mathematical model was carried out by the finite element method using software package *COMSOL Multiphysics 3.5*. Computational domain consisted of 94098 tetrahedral elements (tetrahedrons). The finite element mesh was irregular: the number of elements was increased in the areas of the inlet and output tubes. Piecewise continuous quadratic Lagrange polynomials were used as the basis functions. The relative accuracy of calculations was 0.01. The required degree of discretisation was achieved by incrementally increasing the number of mesh elements and comparing the obtained solutions. If solutions differed slightly the obtained partition was used.

4. VALIDATION OF CFD MODEL

4.1. Reliability of method of solution

Reliability of obtained results was proved by comparing the analytical solution of the problem of the round turbulent jet efflux from the opening and solution, obtained by using the software package *COMSOL Multiphysics 3.5*.

Schlichting and Gersten, (1979) presented analytical solutions obtained by Schlichting and Tolmin as well as experimental points obtained by Reichard. Obtained numerical solutions are consistent with analytical solutions of Tolmin and Schlichting as well as experimental measurements of Reichard (Fig. 2). Thus the results obtained on the basis of analytical solution and those using *COMSOL Multiphysics* are in a good agreement.

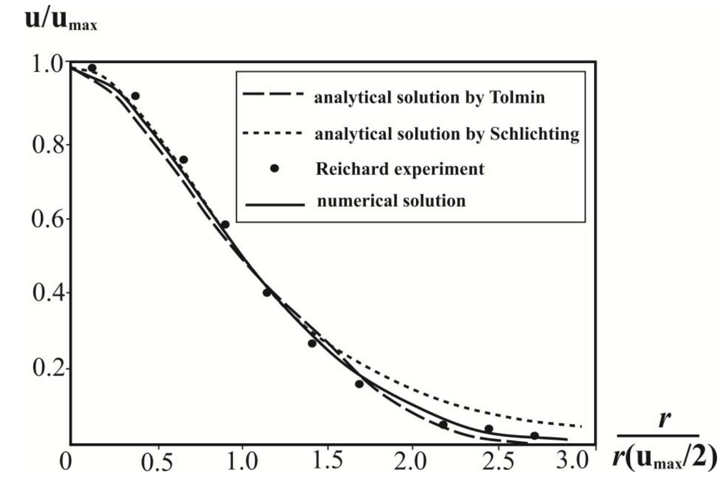

Fig. 2. Distribution of longitudinal velocity component in the round turbulent free jet

4.2. Reliability of model and method of solution

We compared the function of the residence time distribution of flowing particles in the apparatus obtained on the basis of experimental data (Langner, 2009) and numerical calculations to justify reliability of the chosen model and method of solution (Fig. 3).

The experimental setup consists of a cylindrical tank with a horizontal inlet tube in the upper part of the apparatus directed towards the center and output tube at the bottom center. In order to determine the true residence time an indicator is introduced into the flow at the apparatus inlet and indicator concentration is measured as a function of time at the apparatus output.

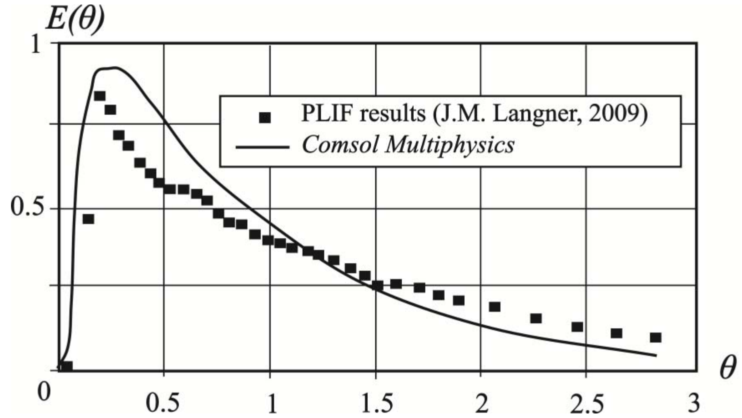

Fig. 3. Residence time distribution function

A passive tracer (rhodamine B) which does not affect the hydrodynamic regime in the apparatus was used as the indicator. A standard pulse signal was used. The experiment was carried out using an optical method of planar laser induced fluorescence (PLIF): the concentration was determined by the luminous intensity of a fluorescent dye dissolved in the working fluid illuminated by a laser knife.

The working area modelled in *COMSOL Multiphysics* is fully consistent with the experimental setup. The calculations were performed on the basis of the mathematical model (1) – (6). The distribution function of the residence time was calculated as follows:

$$E(\theta_i) = HRT \frac{c_i}{\int_0^{t_1} c_i dt}, \ \theta_i = \frac{t_i}{HRT} \tag{8}$$

The mean residence time of flowing particles in the anaerobic digester calculated according to the experimental data is 1.29 and that obtained by calculation is 1.05. A comparative analysis of theoretical and experimental curves showed that the used model adequately describes the hydrodynamic processes occurring in the anaerobic digester.

5. RESULTS

Differences in the mixing systems affect the character of velocity distribution in the anaerobic digester.

A distribution of velocity vector components at different levels of the anaerobic digester with a standard mixing system in the plane x=0 is shown in Fig. 4. Motion of the medium in the lower part of apparatus is determined by the flow through a supply tube that provides considerable excess of the velocity vector component V_x as compared to the components V_y, and V_z (at the level z = 0.1). When z = 0.75, the value of V_z at the center of the anaerobic digester increases as compared to the other velocity vector components. When z = 1.5, the velocity vector component V_y is practically zero. The velocity vector component V_x has its maximum value in the near-bottom region of the apparatus which gradually decreases at its center and increases in the near-wall region at the level of the output tubes while approaching the free surface.

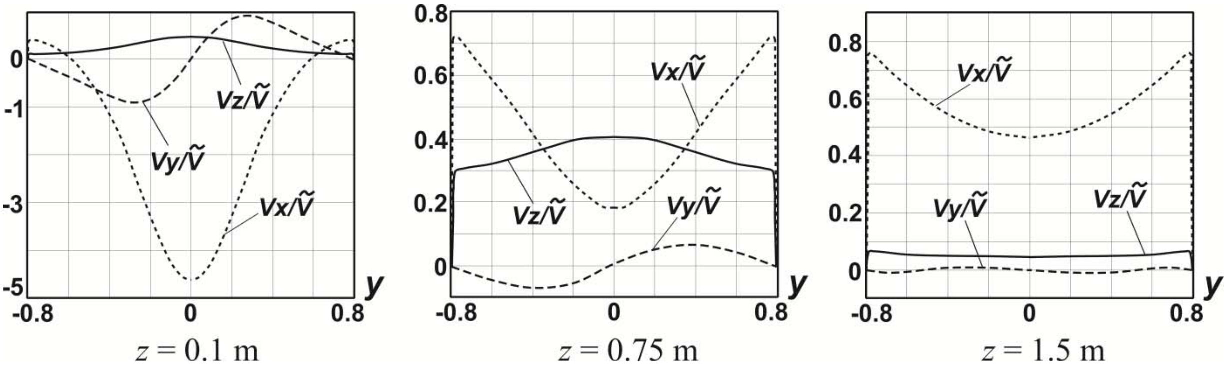

Fig. 4. Distribution of velocity vector components in anaerobic digester with standard mixing system, where $\widetilde{V}$ is the rectified value of velocity in the anaerobic digester

Fig. 5 shows a distribution of velocity vector components at the various levels of anaerobic digester with the modernised mixing system. Fluid motion near the free surface (at the level z = 1.5) and in the central part of the apparatus (at the level z = 0.75) is determined by the longitudinal velocity vector component V_z and at the level of the lower supply tube (at the level z = 0.1) the velocity vector component V_x prevails.

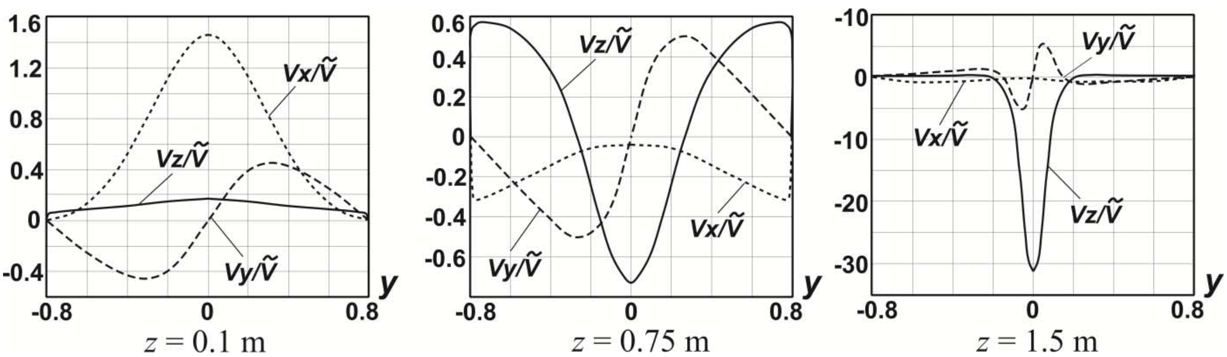

Fig. 5. Distribution of velocity vector components in anaerobic digester with modernized mixing system, where $\widetilde{V}$ is the rectified value of velocity in anaerobic digester

For the considered mixing systems the distribution of solid phase in the anaerobic digester is presented in Figs. 6 and 7. For the standard mixing system at any time and height the concentration of solid particles is higher at the walls than in the center (Fig. 6). This is due to the vertical currents along the walls carrying solid sediment particles and sludge blankets (Fig. 4).

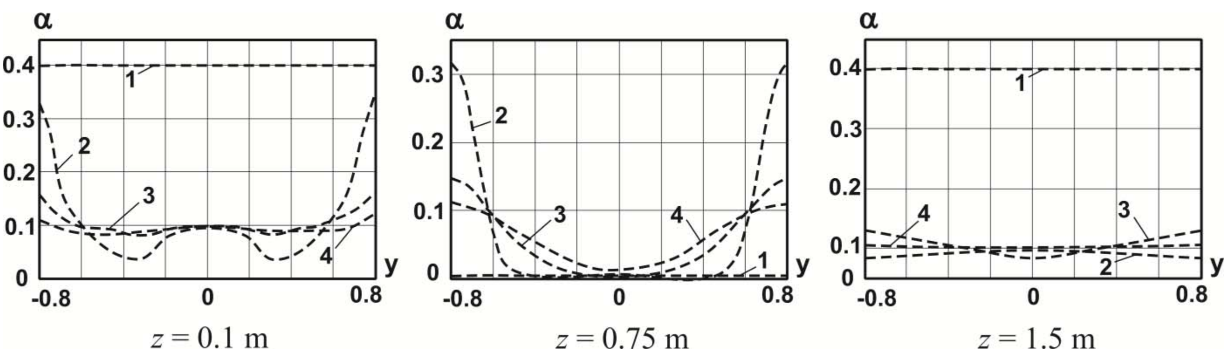

Fig. 6. Dynamics of change in concentration fields for anaerobic digester with standard mixing system:
1 – 0 s; 2 – 500 s; 3 – 1500 s; 4 – 2500 s

For the modernised system a similar distribution occurs only in the lower layers (Fig. 7, z = 0.1) in which the jet from the upper tube has practically no effect (Fig. 5 the value of $V_z/\widetilde{V}$ is significantly smaller than other components). When the jet from the upper tube reaches the central part of the modernised system, the concentration distribution in its central part increases (curve 2 in Fig. 7, z = 0.75). Further, due to the fact that in the near-wall region the flow moves upwards ($V_z/\widetilde{V}$ >0 in the near-wall region Fig. 5) carrying the sediment the concentration distribution has the form of curves 4 and 3 in Fig. 5. In the upper part the concentration distribution is influenced by the presence of sludge blanket (curve 1, Fig. 7, z = 1.5) which is washed away over time (curves 2 and 3). Afterwards under the action of the upward flows along the walls carrying solid particles from the bottom the concentration distribution takes the form of the curve 4.

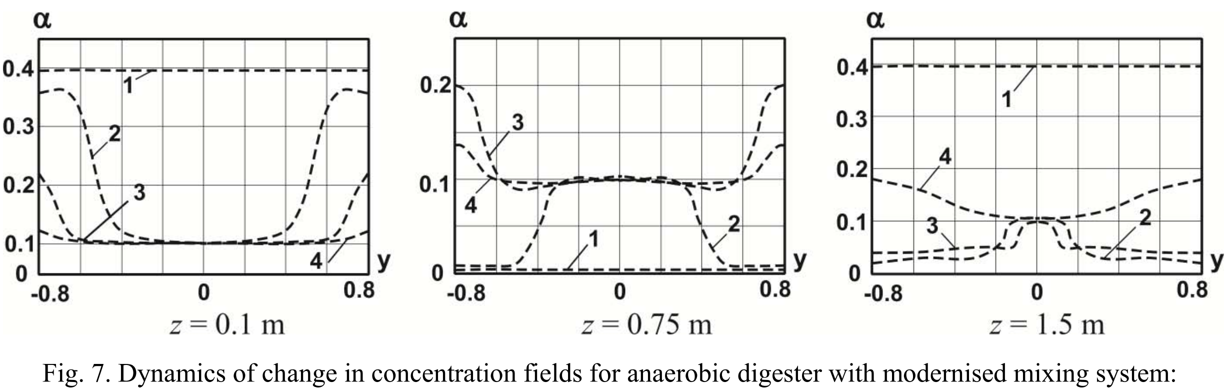

Fig. 7. Dynamics of change in concentration fields for anaerobic digester with modernised mixing system:
1 – 0 s; 2 – 500 s; 3 – 1500 s; 4 – 2500 s

The obtained data on distribution of the velocity and concentration fields in the anaerobic digester represent a picture of hydrodynamic and mixing processes in the apparatus. However, it is necessary to use a quantitative evaluation criterion to obtain particular data on mixing quality.

A criterion QM which takes into account kinetics of methanogenesis was used to evaluate the mixing quality in anaerobic digester:

$$QM = \frac{\bar{\delta}(t)}{\delta_{\max}} \tag{9}$$

$$\bar{\delta}(t) = \frac{1}{W}\sum_{i=1}^{N}\frac{B_0\rho(\alpha_i)\alpha_i}{HRT}\left(1-\frac{K(\alpha_i)}{HRT\mu_{\max}-1+K(\alpha_i)}\right)\cdot W_i \tag{10}$$

$$\delta_{\max} = \frac{B_0\rho(\alpha_1)\alpha_1}{HRT}\left(1-\frac{K(\alpha_1)}{HRT\mu_{\max}-1+K(\alpha_1)}\right) \tag{11}$$

The maximum possible value of mixing quality index *QM* is equal to 1 which corresponds to the state of complete homogeneity of the substrate in the anaerobic digester.

Under hydraulic mixing starting from some point in time the process becomes stabilised as indicated by the behaviour of the mixing quality criteria (Fig. 8). As the mixing time we will call the minimum time t_m starting from a point when the change of *QM* in time is less than 1%.

When using the modernised mixing system for a period of 42 min. index *QM* is close to 1 (mixing quality index *QM* = 0.9899), that is by 18% higher than in the anaerobic digester with the standard mixing system (Fig. 8). With further mixing the value of index *QM* stabilises.

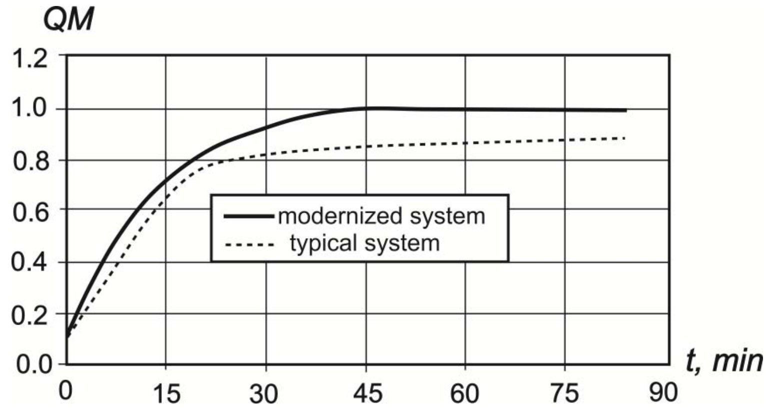

Fig. 8. Dynamics of *QM* in anaerobic digester

Thus, when using the modernised mixing system, the mixing time is 42 min. and when using the standard mixing system – 83 min. (mixing quality index *QM* = 0.8835).

5.1. Impact of geometrical parameters of anaerobic digester on mixing quality

Obviously, the efficiency of the modernised mixing system compared to the standard one depends on the geometrical proportions of the reactor. Therefore, numerical investigations of the anaerobic digesters with various geometrical parameters were carried out. Criterion *QM* was used to determine the mixing efficiency.

Comparative evaluation of mixing time when using the standard and modernised mixing systems in the range of ratios of height to diameter of the anaerobic digester $0.23 \leq H/D \leq 1.2$ was carried out with the same power consumed for pumping the organic substrate (Fig. 9). Specific power spent on mixing of 1 m^3 of the substrate is the same for the compared mixing systems.

The proposed modernised system of hydraulic mixing is efficient and suitable for anaerobic digesters within the considered range of ratios *H/D* = 0.23÷1.2, since it enables to reduce the time required to achieve a given mixing quality which leads to a substantial decrease of operating time of the system as well as providing savings of electrical energy. The maximum effect of using the modernised mixing system is observed for anaerobic digesters with a ratio *H/D* from 0.7 to 1. The time required for mixing in these apparatuses is two times smaller than that in the similar anaerobic digesters with a standard mixing system.

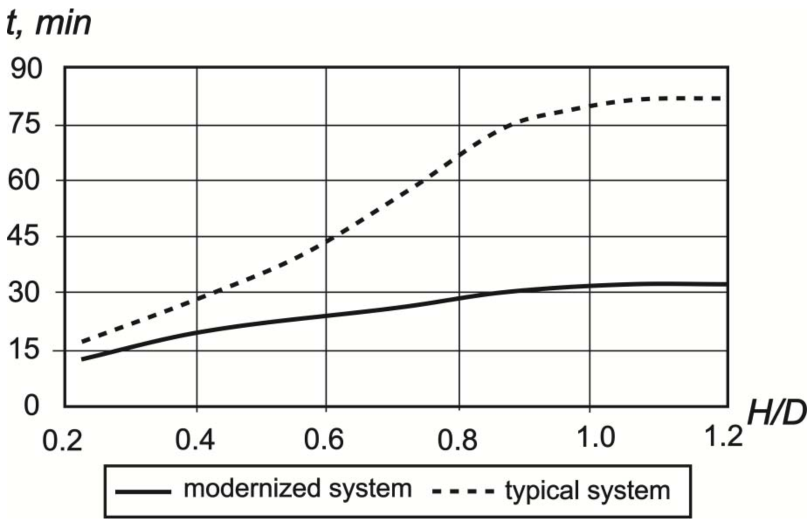

Fig. 9. Mixing time when using standard and modernised mixing systems depending on *H/D*

The graphs shown in Fig. 10 allow to evaluate the mixing time depending on the process parameters (specific power, flow rate, proportions of the reactor) when using the modernised mixing system. Using the similarity theory the results of numerical studies can be transferred on anaerobic digesters with a diameter of up to 22 m (anaerobic digester volume of 10000 m^3). Thus, the obtained nomogram allows us to determine the mixing time as well as power of the circulating pump and circulating pump flow (Fig. 10 shows specific power *N* spent on mixing of 1 m3 of the substrate) in an anaerobic digester characterised by *H/D*.

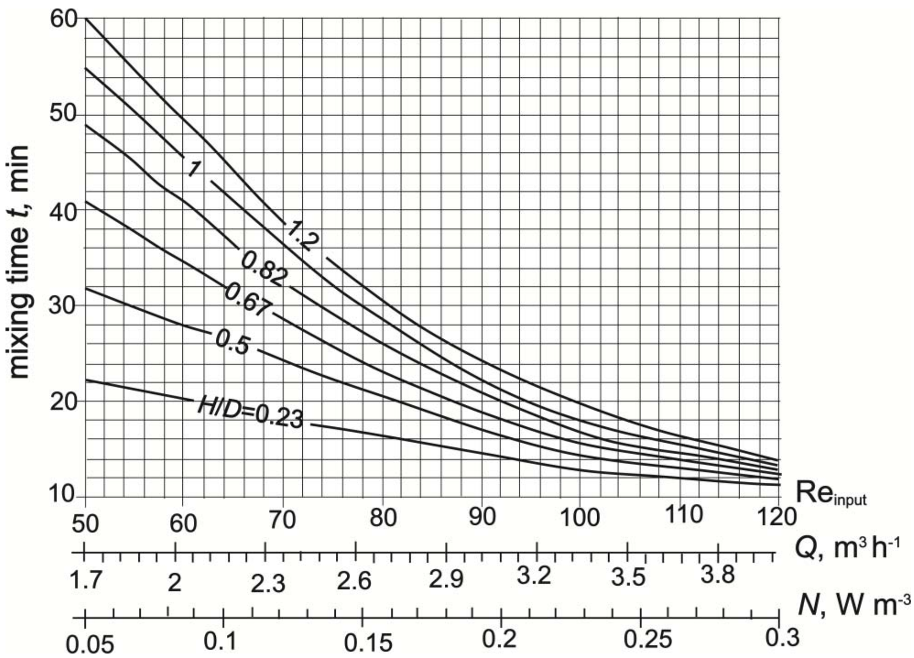

Fig. 10. Characteristics of the modernised system of hydraulic mixing (*H/D* – ratio of height to diameter of anaerobic digester)

Obtained data are recommended for use when designing an anaerobic digester construction and technological operating parameters of a hydraulic mixing system.

6. CONCLUSIONS

The carried out numerical studies of the proposed modernised system of hydraulic mixing demonstrated its advantages over the standard one.

The proposed modernised system of hydraulic mixing is efficient and suitable for anaerobic digesters within the considered range of ratios $H/D = 0.23 \div 1.2$, since it enables to reduce the time required to achieve a given mixing quality which leads to a substantial decrease of operating time of the system as well as providing savings of electrical energy. The maximum effect of using the modernised mixing system is observed for anaerobic digesters with a ratio H/D from 0.7 to 1. The time required for mixing in these apparatuses is two times smaller than that in the similar anaerobic digesters with a standard mixing system.

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SYMBOLS

b	parameter characterising the approximation width of layer height h_0
B_0	maximum biogas yield from a unit of organic matter, $m^3\,kg^{-1}$
$C\mu$, $C_{\varepsilon1}$, $C_{\varepsilon2}$	empirical constants of turbulent model k - ε
c_i	concentration of fluorescent fluid at the output
D	digester diameter, m
$\mathbf{D}$	strain rate tensor, s^{-1}
d_p	diameter of circulation tubes, m
E	residence time distribution function
$\overline{g}$	gravity vector, $m\,s^{-2}$
H	digester height, m
h_0	layer height, m
h_1	distance from the apparatus bottom to the center of the bottom discharge tube, m
h_2	distance from the apparatus bottom to the center of the upper supply tube, m
HRT	hydraulic retention time of the substrate, day
$\mathbf{I}$	identity tensor
k	turbulent kinetic energy, J
K	kinetic coefficient
N	specific power, $W\,m^{-3}$
n	normal line to the solid and open boundaries
n_1	normal line to the boundary corresponding to the output
$\overline{n}$	normal vector to the substrate surface
p	pressure, Pa
p_g	gas pressure, Pa
Q	volumetric flow rate, $m^3\,h^{-1}$
QM	mixing criterion
Re_{input}	Reynolds number characterizing the flow in an inlet tube
$\mathbf{T}$	strain tensor, $Pa\,m^{-2}$
T	temperature, °C
t	time, s

u	longitudinal velocity component in the round turbulent free jet, m s^{-1}
u_{max}	maximum value of u, m s^{-1}
$\overline{V}$	velocity vector, m s^{-1}
$\overline{V}_0$	initial velocity vector, m s^{-1}
V_x, V_y, V_z	velocity components, m s^{-1}
$\widetilde{V}$	rectified value of velocity, m s^{-1}
W	digester volume, m^3
x, y, z	Cartesian coordinates

Greek symbols

α	volume fraction (concentration) of dispersion medium
α_1	optimal volume concentration, m^{-3}
$\alpha_{\max}$	the greatest possible volume concentration of the dispersed phase
$\delta_{\max}$	maximum intensity of biogas yield, m^3 biogas m^{-3} substrate day^{-1}
$\overline{\delta}(t)$	mean intensity of biogas yield, m^3 biogas m^{-3} substrate day^{-1}
ε	dissipation of turbulent kinetic energy, J s^{-1}
θ	dimensionless time
θ_i	residence time of flow particles in the apparatus
$\mu_{\max}$	maximum growth rate of microorganisms, day^{-1}
μ_e	viscosity of the organic substrate, Pa s
μ	molecular viscosity, Pa s
μ_T	turbulent viscosity, Pa s
ρ	density of organic substrate, kg m^{-3}
ρ_1	density of the carrier phase, kg m^{-3}
ρ_2	density of the dispersed phase, kg m^{-3}
σ_k, σ_ε	empirical constants of turbulent model

REFERENCES

Chmielewski A.G., Berbec A., Zalewski M., Dobrowolski A., 2012. Hydraulic mixing modeling in reactor for biogas production. *Chemical and Process Engineering*, 33, 621-628. DOI: 10.2478/v10176-012-0052-8.

Chmielewski A.G., Urbaniak A., Wawryniuk K., 2013. Membrane enrichment of biogas from two-stage pilot plant using agricultural waste as a substrate. *Biomass Bioenergy*, 58, 219–228. DOI: 10.1016/j.biombioe.2013.08.010.

Giunter L.I., Goldfarb L.L., 1991. *Anaerobic Digesters*. Stroyizdat, Moscow, 44.

Huang R., Long Y., Luo T., Mei Z., Wang J., Long E., 2014. The research on optimization of the multiphase flow field of biogas plant by using CFD software. *J. Energy Power Eng*., 8, 1038-1046.

Kamarad L., Pohn S., Bochmann G., Harasek M., 2013. Determination of mixing quality in biogas plant digesters using tracer tests and computational fluid dynamics. *Acta Univ.Brunensis,* LXI, 5, 2013, 1269-1278. DOI: 10.11118/actaun201361051269.

Karaeva J.V., Trakhunova I.A., Khalitova G.R., 2012. Installation of anaerobic digestion of organic waste. Patent number 115350 of the Russian Federation (in Russian).

Karim K. Hoffman R., Klasson T.K., Al-Dahhan M.H., 2005. Anaerobic digestion of animal waste: Effect of mixing. *Water Res.*, 39, 3597-3606. DOI: 10.1016/j.watres.2005.06.019.

Langner J.M., 2009. *MSci thesis*. University of Manitoba, Winnipeg, Canada, 148.

Latha S., Borman D., Sleigh P.A., 2009. CFD multiphase modeling for evaluation of gas mixing in an anaerobic digester. *14th European Biosolids and Organic Resources Conference and Exhibition.* Leeds, UK, 2009.

Maier C., Weichselbaum W., Schlerka M., Harasek M., 2010. Development of agitation systems in biogas plants: Investigation of mixing characteristics, improvement of energy efficiency and scale-up using CFD. *Chem. Eng. Transactions*, 21, 1195-1200. DOI: 10.3303/CET1021200.

Mândrea L., Băran G., Cănănău S., Băbutanu C.A, 2011. The suspensions dynamics in biogas reactors. *U.P.B. Sci. Bull., Series D,* 73, 121-130.

Mendoza A.M., Martinez T.M., Montanana V.F., Jimenez P.A.L., 2011. Modeling flow inside an anaerobic digester by CFD techniques. *IJEE*, 6, 963-974.

Meroney R.N. Colorado P.E., 2009. CFD simulation of mechanical draft tube mixing in anaerobic digester tanks. *Water Res.*, 43, 1040-1050. DOI: 10.1016/j.watres.2008.11.035.

Palige J., Rudniak L., Dobrowolski A., Zalewski M., Chmielewski A.G., 2011. Optymalizacja parametrów mieszania biozawiesiny w fermentorze z wykorzystaniem metody CFD. *Inż. Ap. Chem*., 50, 82-83 (in Polish).

Schlichting H., Gersten K., 1979. *Boundary-layer theory*. McGraw Hill, New York, 749.

Sindall R., Bridgeman J., Carliell-Marquet C., 2013. Velocity gradient as a tool to characterise the link between mixing and biogas production in anaerobic waste digesters. *Water Sci. Technol.*, 67, 2800-2806. DOI: 10.2166/wst.2013.206.

Terashima M., Goel R., Komatsu K., Yasui H., Takahashi H., Li Y.Y., Noike T., 2009. CFD simulation of mixing in anaerobic digesters. *Bioresour. Technol*., 100, 2228–2233. DOI: 10.1016/j.biortech.2008.07.069.

Vesvikar M.S., Al-Dahhan M., 2005. Flow pattern visualization in a mimic anaerobic digester using CFD. *Biotechnology and Bioengineering*, 89, 719-732. DOI: 10.1002/bit.20388.

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