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The Influence of Sludge on Thermal Performance of Heat Exchanger Tubes Inside in an Anaerobic Digester

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1. Introduction

In recent times, we have been observing an increase in energy demand, which results in the deepening devastation of the natural environment. One of the effective ways to mitigate this phenomenon is the use of biogas plants (Wandera et al. 2018). Biogas plants in which waste is used as an alternative source of energy as opposed to sources of conventional energy sources makes these green technologies as pro-ecological investments. By using waste after sewage treatment and agricultural waste (Kogut et al. 2012, Montusiewicz 2014, Sadecka & Suchowska-Kisielewicz 2016), biogas plants contribute to the improvement of the quality of the environment, which makes them an integral part of environmental protection. The Polish government program "Innovative Energy – Powering Agriculture" assumes that by 2020 one biogas plant will be built in each municipality. However, this goal is very difficult to implement currently. According to the data of the Energy Regulatory Office – Department of Renewable Energy, there are approximately only 300 biogas plants in Poland (data from September 30, 2016). About 30% of these facilities are the agricultural type. For comparison, in China there were more than 30 000 middle and large agricultural biogas plants in 2010 (Guo et al. 2013). However, it can be stated that there is a continuous increase in the power of installations using biogas in Poland (Fig. 1).

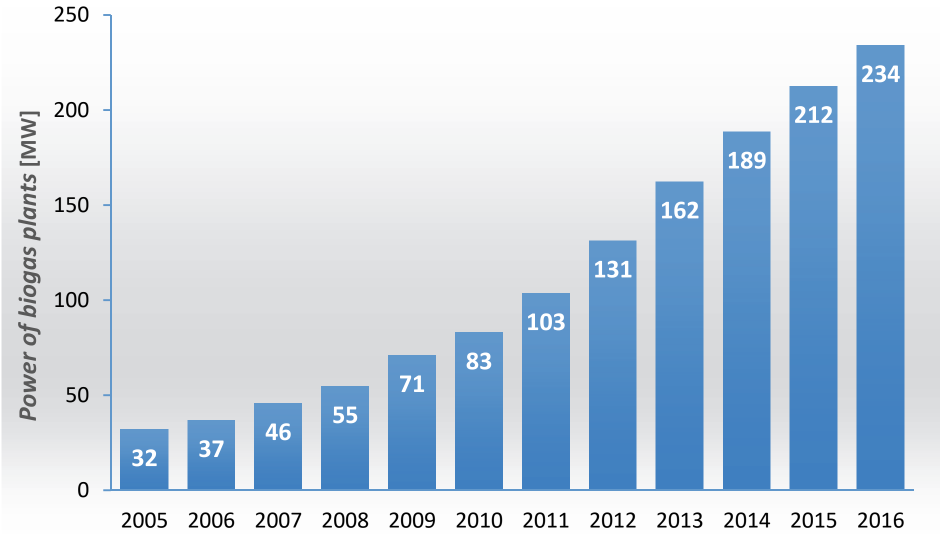

Fig. 1. Installed capacity for power generation in biogas plants in Poland (prepared on the basis of data from the Energy Regulatory Office – Department of Renewable Energy)
Rys. 1. Zainstalowana moc do wytwarzania energii w biogazowniach w Polsce (przygotowana na podstawie danych Urzędu Regulacji Energetyki – Departament Źródeł Odnawialnych)

According to Igliński et al. (2015), the energy amount that can potentially be obtained from biogas in Poland is around 11 million MWh. This potential is made up of 82 million m^3 of municipal waste, 20 million m^3 sewage sludge, 1 600 million m^3 of farm animal droppings, and, according to Piwowar et al. (2016), over 244 million m^3 of all agricultural biogas production plants per year.

One of the most important problems related to the operation of biogas plants in Poland is the drop in the temperature of the bed at times of low temperature of the outdoor air. A frequent cause of this phenomenon is the insufficient power of the heat exchanger placed inside the anaerobic digester. This article analyses the impact of sludge on decreasing the heat transfer efficiency in these devices.

Teng et al. (2017) investigated the effect of mineral scale deposition on heat exchanger pipes. They experimentally tested the progressive build-up of deposits, the rate of deposition, and the crystal morphology of the mineral deposits on tubes made of stainless and carbon steel, brass, copper, and aluminium. In this work, many interesting conclusions were given allowing the optimal design of heat exchangers operating in difficult conditions.

The phenomenon of the deposition of organic and inorganic compounds in heat exchangers used in refineries was studied by Diaz-Bejaranoa et al. (2017). They developed a model based on thermo-hydraulic methodology, which was used to analyse the operation of shell-and-tube heat exchangers. The authors of this research stated that the new comprehensive model can be a very useful tool for diagnosis, monitoring, and troubleshooting of fouling in refinery heat exchangers.

Heat pumps are often used for energy recovery from urban wastewater. Unfortunately, the microbiological contaminants in sewage negatively affect the operation of the heat exchangers. The influence of many factors on the fouling formation by iron and sulphate-reducing bacteria were analysed by Xiao et al. (2018). The researchers formulated a number of conclusions regarding the effect of microbial fouling on the efficiency of heat exchangers.

Markowski et al. (2013) developed a new calculation algorithm for determination of the thermal resistance of fouling on heat exchangers. This method was validated by comparison calculation results with measurement data obtained from a heat exchanger connected to a distillation system. As the authors claim, applying of this algorithm and methodology can help in determining of fouling thermal resistance and its influence on the thermal performance of heat exchangers used in industry.

One important problem of a biogas plant is to maintain a constant temperature inside the fermentation chamber, especially during the winter. The basic component responsible for setting a constant temperature inside the digester is the heat exchanger. Operation of this device may be disturbed by deposition of sludge on the external heat transfer surface. As it turned out, in the literature there is no information nor any research results related to the operation of heat exchangers used in an anaerobic digester. The purpose of this work is to investigate the influence of sludge accumulation on the efficiency of the heat transfer process.

2. Description of the research object under investigation

The biogas plant (Fig. 2), located near the village of Ryboly (Poland), consists of two anaerobic digesters, a storage tank, co-generator and an administrative building.

Fig. 2. The storage tank and fermentation chamber located in the Ryboly Biogas Plant
Rys. 2. Zbiornik i komora fermentacyjna w biogazowni w Rybołach

The research object consists of four heating loops connected in parallel. These are made of stainless steel pipes with an outer diameter of 60.3 mm and a wall thickness equal to 2 mm. The entire construction of the heat exchanger is attached to the walls of the tank in its lower part, as shown in Fig. 3a. Supply and return manifolds (Fig. 3b) are placed on the external wall of the chamber. Photos on Figs. 3a and 3b were taken during the installation of two additional heating loops in autumn 2017, after the analysis demonstrating the insufficient power of the heat exchanger when there is a low external temperature.

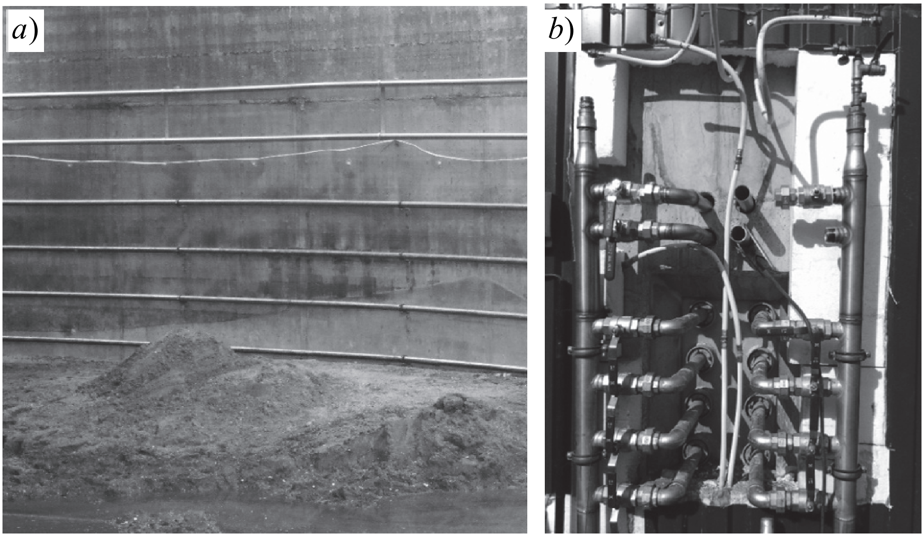

Fig. 3. Heat exchanger in Ryboly Biogas Plant: (a) heat exchanger attached to the digester wall (deposits formed during the operation of the digester are visible at the bottom of the chamber), (b) manifolds during mounting of two additional loops of the heat exchanger
Rys. 3. Wymiennik ciepła w biogazowni w Rybołach: (a) wymiennik ciepła przymocowany do ściany komory fermentacyjnej (osady powstałe podczas pracy komory fermentacyjnej są widoczne w dolnej części komory), (b) rozdzielacz podczas montażu dwóch dodatkowych pętli wymiennika ciepła

3. Model of determining the influence of sludge on the thermal performance of the heat exchanger

In order to determine the influence of sludge thickness on the thermal efficiency of the exchanger, a forced convection heat transfer model for the external and internal flow was used. The physical model of the heat exchanger is shown in Fig. 4. The following assumptions were made for the computer simulations: steady-state conditions, fully developed flow, incompressible liquid, and negligible viscous dissipation. Additionally, it was assumed that the sludge uniformly covers the walls of the heat exchanger tubing in such a way that it creates an additional layer of cylindrical wall with diameter d_3 (Fig. 4). Tab. 1 presents the basic geometric data of the heat exchanger (one loop) and the properties of the working medium and substrate.

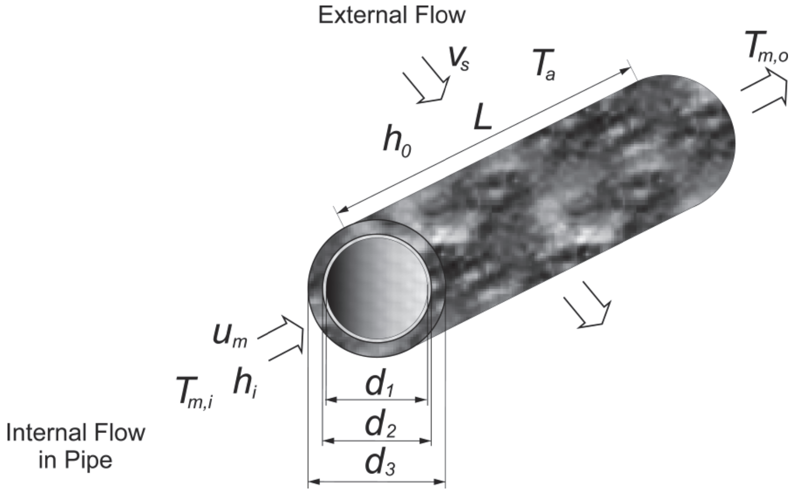

Fig. 4. Physical model of the heat exchanger
Rys. 4. Model wymiennika ciepła

The Reynolds number of the flow inside the heat exchanger is described by the following formula:

$$\mathrm{Re}_{d_1} = \frac{4m}{\pi d_1 \mu_m} \tag{1}$$

Therefore, assuming a fully developed flow (Re = 26393) through the heat exchanger, the convection coefficient h_i can be determined from the definition of the Nusselt number (2) and the Dittus-Boelter correlation (3):

$$h_i = \frac{\mathrm{Nu}_{d_1} k_m}{d_1} \tag{2}$$

$$\mathrm{Nu}_{d_1} = 0.023\,\mathrm{Re}_{d_1}^{4/5}\,\mathrm{Pr}^{0.3}, \quad \mathrm{Re}_{d_1} \geq 10000, \quad 0.6 \leq \mathrm{Pr} \leq 1600,$$
$$\mathrm{Pr} = \frac{c_{pm}\mu_m}{k_m} \tag{3}$$

The Churchill-Bernstein correlation was used for determination of the external convective heat transfer coefficient h_o:

$$h_o = \frac{\mathrm{Nu}_{d_3} k_s}{d_3} \tag{4}$$

$$\mathrm{Nu}_{d_3} = 0.3 + \frac{0.62\,\mathrm{Re}_{d_3}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(0.4/\mathrm{Pr}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}_{d_3}}{282000}\right)^{5/8}\right]^{4/5}, \tag{5}$$

$$\mathrm{Re}_{d_3}\mathrm{Pr} \geq 0.2$$

where the Reynolds number (6) and the Prandtl number (7) are defined as:

$$\mathrm{Re}_{d_3} = \frac{\rho_s \mathrm{v}_s d_3}{\mu_s} \tag{6}$$

$$\mathrm{Pr} = \frac{c_{ps}\mu_s}{k_s} \tag{7}$$

where v_s is the substrate velocity around the heat exchanger tubes.

The temperature at the outlet from the exchanger was determined according to the following relationship (Bergman et al. 2011):

$$T_{m,o} = T_a - \left(T_a - T_{m,i}\right)\exp\left[-\frac{\pi d_1 L}{m c_{pm}} U\right],\ \left[{}^{o}\mathrm{C}\right] \tag{8}$$

where an overall heat transfer coefficient is defined as:

$$U = 1\Big/\left(\frac{1}{h_i} + \frac{r_1}{k_w}\ln\frac{r_2}{r_1} + \frac{r_1}{k_{sl}}\ln\frac{r_3}{r_2} + \frac{r_1}{r_3}\frac{1}{h_o}\right),\ \left[\frac{\mathrm{W}}{m^2\,{}^{o}C}\right] \tag{9}$$

where $r_1=d_1/2$, $r_2=d_2/2$ and $r_3=d_3/2$ (Fig. 5).

The total heat transfer rate of the heat exchanger is determined by the formula:

$$q = m c_{pm}\left(T_{m,o} - T_{m,i}\right),\ [\mathrm{W}] \tag{10}$$

Two issues were considered to investigate the influence of the sludge on the heat transfer rate of the heat exchanger. In the first case, two examples were solved. The first example is the dependence of the outlet temperature from the exchanger as a function of the thickness of the sludge on the piping and the thermal conductivity of the sludge at a constant substrate velocity. The second example is the dependence of the thermal efficiency of the heat exchanger as a function of the thickness of the sludge on the piping and the thermal conductivity of the sludge at a constant substrate velocity.

Table 1. Parameters used to calculate the influence of sludge on the thermal efficiency of the exchanger installed in the digester
Tabela 1. Parametry stosowane do obliczania wpływu osadu na wydajność cieplną wymiennika zainstalowanego w komorze fermentacyjnej

Description	Symbol	Value	Unit
Inner diameter of the heat exchanger	d_1	0.0563	m
Outer diameter of the heat exchanger	d_2	0.0603	m
Thickness of the sludge layer on the heat exchanger	s	0.005-0.01	m
Mass flow of heat exchanger medium	m	0.594	kg/s
Length of a single heat exchanger loop in the digester	L	94.25	m
Inlet temperature for the heat exchanger	T_{mi}	70	^{o}C
Temperature substrate in the fermentation chamber	T_a	40	^{o}C
Specific heat capacity of the working medium in the exchanger	c_{pm}	4180	J/kg/^{o}C
Dynamic viscosity of the working medium in the exchanger	μ_m	0.000509	kg/m/s
Thermal conductivity of the working medium in the exchanger	k_m	0.64	W/m/K
Thermal conductivity of the steel wall of the heat exchanger (1.4301 Austenitic Corrosion Resistant Steel)	k_w	15	W/m/K
Thermal conductivity of the sludge on the heat exchanger	k_{sl}	0.2-1.1	W/m/K
Specific heat capacity of the substrate	c_{ps}	4184	J/kg/^{o}C
Dynamic viscosity of the substrate	μ_s	0.03	kg/m/s
Thermal conductivity of the substrate	k_s	0.62	W/m/K
Substrate velocity in the fermentation chamber	v_s	0.001-0.1	m/s

In the second issue, the temperature at the outlet from the exchanger and heat transfer rate of the heat exchanger were determined as a function of the velocity of the substrate around the heat exchanger tubing at a constant thermal conductivity of the sludge. The properties of the working medium (water) in the heat exchanger were assumed for the average inlet and outlet temperature (Tab. 1).

The thickness of the sludge appearing on the piping changes with the time of operation of the digester. In the case of the tested real object, after three years of exploitation of the digester the thickness of the sludge layer was about 1 cm (Fig. 5a). The view of the exchanger after purification from the sludge on the piping wall is presented on Fig. 5b. The heat transfer coefficient, specific heat and sludge viscosity depend on the type of substrate used in the digester. The substrate properties presented in Tab. 1 were adopted on the basis of tests carried out by the manager of the biogas plant in Ryboly, while the sludge properties for different substrate forms were adopted on the basis of literature data (Poloski et al 2002, Dewil et al. 2007, Wu 2013, Terradas et al 2014).

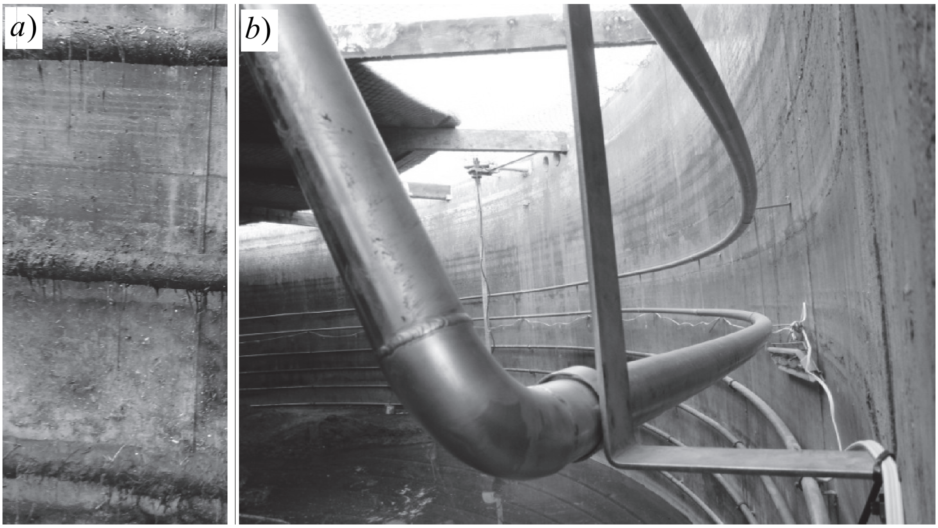

Fig. 5. Piping of the heat exchanger in the digester: (a) after three years of operation, (b) view after cleaning the exchanger
Rys. 5. Orurowanie wymiennika ciepła w komorze fermentacyjnej: (a) po trzech latach eksploatacji, (b) widok po oczyszczeniu wymiennika

The mass flow rate through the heat exchanger was determined on the basis of actual measurements and amounted to 0.594 kg/s. Due to the lack of the ability to measure the flow velocity of the substrate around the piping, the velocity range from 0.001 to 0.1 m/s was adopted based on the literature results (Meroney & Colorado 2009, Bridgeman 2012, Babarinsa et al 2013, Wu 2014).

4. Results and discussion

The effect of various fouling from the working medium inside the piping on the operation of heat exchangers was described extensively in the literature (Mitrovic 2012). There are no studies on the influence of sludge from the working substrate on the thermal efficiency of the heat transfer in the digester chamber. In 2015-2017, the heat demand of the fermentation chambers and outside temperature were measured. Fig. 6a shows the average monthly outside temperature in 2015-2017 near biogas plants, which did not differ significantly in subsequent years, while Fig. 6b shows the average annual energy for heating the fermentation chambers in the same range of years. Energy consumption for heating purposes in 2016 was higher by 12.66% than in 2015, while in 2017 energy consumption was higher by 12.06% than in 2016. According to the authors, the increasing trend of heat consumption for heating the substrate in the digester is probably related to the increase in thermal resistance of heat transfer.

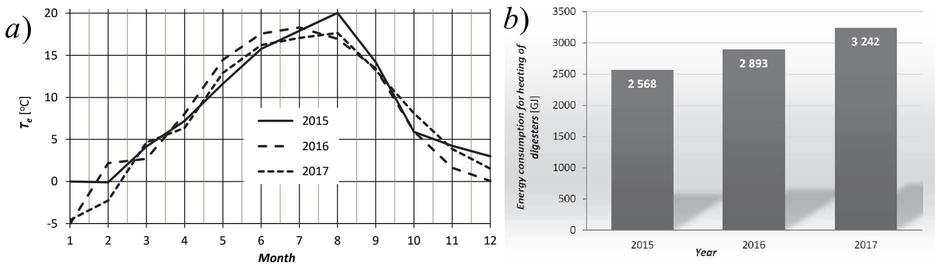

Fig. 6. The results of tests of the heat exchangers inside the digesters in Ryboly: (a) average monthly outdoor temperatures measured in 2015-2017 near the biogas plant, (b) energy consumption for heating of digesters in 2015-2017
Rys. 6. Wyniki badań wymienników ciepła wewnątrz komór fermentacyjnych w Rybołach: (a) średnie miesięczne temperatury zewnętrzne mierzone w latach 2015-2017 w pobliżu biogazowni, (b) zużycie energii do ogrzewania komór fermentacyjnych w latach 2015-2017

Figs. 7a-b show the dependence of the outlet temperature from the heat exchanger (Fig. 7a) and the heat transfer rate of the exchanger (Fig. 7b) depending on the thickness of the sludge layer and the thermal conductivity coefficient of the sludge. For the calculations a constant flow velocity of the substrate v_s = 0.001 m/s, and the following thermal conductivity coefficients of the sludge were assumed: 0.3, 0.5, and 1.0 W/(mK). Along with the increase of the thickness of the sludge layer on the exchanger wall, the outlet temperature from the exchanger rises, which leads to the decrease in the heat transfer rate of the exchanger. For example, an increase of the sludge layer from 0.002 to 0.01 m with a thermal conductivity coefficient of 0.5 W/(mK) leads to a decrease in thermal efficiency by 47%.

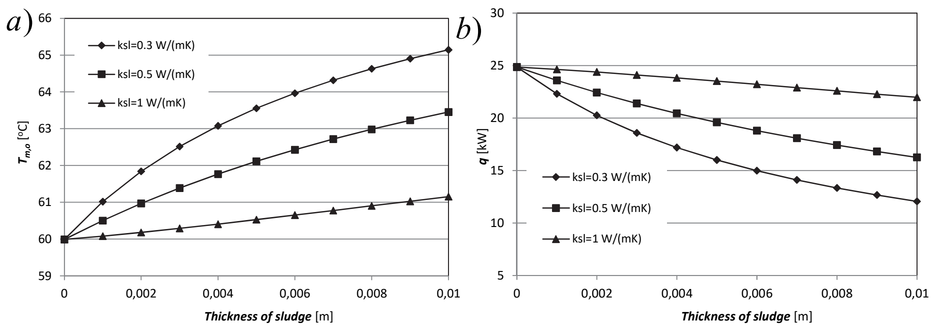

Fig. 7. Change of the heat exchanger operation parameters depending on the thickness of the sludge layer *s* and the thermal conduction coefficient of the sludge k_s: (a) $T_{m,o}=f(s)$, (b) $q=f(s)$

Rys. 7. Zmiana parametrów pracy wymiennika ciepła w zależności od grubości warstwy osadu i współczynnika przewodzenia ciepła osadu k_s: (a) $T_{m,o}=f(s)$, (b) $q=f(s)$

The next charts show the dependence of outlet temperature from the heat exchanger (Fig. 8a) and the heat transfer rate (Fig. 8b) depending on the substrate velocity around the heat exchanger tubing and the thickness of the sludge layer. A constant thermal conductivity coefficient of the sludge (k_s=1 W/(mK), piping of the exchanger without sludge, and the heat exchanger with sludge-thickness 0.005 m and 0.01 m were assumed for calculations. As the velocity of the substrate increases, the outlet temperature from the exchanger decreases, while the heat transfer rate increases. In the case of the increase in the thickness of the sludge, the characteristics $T_{m,o}=f(v_s)$ rise, i.e. the outlet temperature from the exchanger increases, while the reverse effect can be observed in the case of $q=(v_s)$. Figs. 8a and 8b show that the increase in substrate velocity around the piping increases heat transfer. It should be noted that the tested exchanger is installed close to the wall of the fermentation chamber. In this case the substrate velocity, according to the literature (Poloski et al 2002, Dewil et al. 2007, Wu 2013, Terradas et al 2014), is not too high.

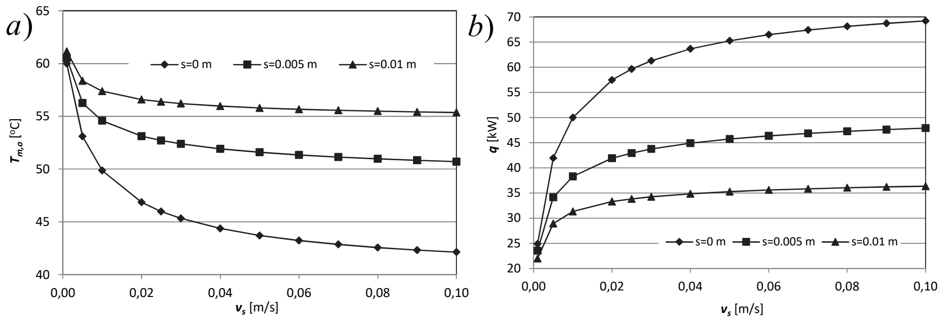

Fig. 8. Changing the parameters of the heat exchanger operation depending on the substrate velocity for different sludge layer thicknesses *s*: (a) $T_{m,o}=f(v_s)$, (b) $q=f(v_s)$

Rys. 8. Zmiana parametrów pracy wymiennika ciepła w zależności od prędkości przepływu substratu dla różnych grubości warstw osadu s: (a) $T_{m,o}=f(v_s)$, (b) $q=f(v_s)$

5. Conclusion

The reason for writing this article were problems related to the operation of the biogas plant in Ryboly during the winter season. The paper presents the model for determining the influence of sludge on the operation of the heat exchanger in the anaerobic digester depending on the geometry, operating parameters, and fouling properties. This approach was implemented in the form of a computer program that allows one to specify the influence of sludge on the pipe walls on the efficiency of the heat exchanger inside the anaerobic digester. Based on the simulations and the results of measurements, the following conclusions can be drawn:

1. The existence of sludge on the external walls of the heat exchanger causes a decrease in the thermal efficiency of the heat transfer. It should be noted here that increasing the supply temperature of the heat exchanger in order to overcome the effects of lowering the heat

transfer can lead to the death of microorganisms around the heating system as a result of local excessive increase of substrate temperature. One of the possible solutions to this problem is to increase the heat exchange surface by adding additional loops of tubes in the existing biogas plant.

2. The increase in flow rate around the piping in the fermentation chamber increases the heat transfer between the exchanger and the substrate. Therefore the negative effect of the fouling layer on the heat transfer can be overcome by increasing the velocity around the piping by intensifying the reactor mixing process e.g. by increasing the rotational speed of agitators in the anaerobic digester.
3. The thermal conductivity of the fouling depends on the type of working substrate in the digester. This coefficient has a direct effect on the efficiency of the heat exchanger. The subject of the influence of the substrate sludge on the external surface of the heat exchanger in the anaerobic digester is new, and therefore requires further testing for different types of substrates. However, it should be noted that implementing this type of an experimental research in such a difficult environment is highly complex and expensive.

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Wpływ osadu na wydajność cieplną wymiennika ciepła w beztlenowej komorze fermentacyjnej

Streszczenie

Biogazownie w Polsce są obecnie jednym z najbardziej dochodowych alternatywnych źródeł energii. Wysoką wydajność biogazowni zapewnia przede wszystkim odpowiedni dobór wymienników ciepła w beztlenowej komorze fermentacyjnej. W literaturze brak jest danych dotyczących działania wymienników ciepła stosowanych w beztlenowej komorze fermentacyjnej. Osad w komorze fermentacyjnej często osadza się na rurach wymiennika ciepła, zmniejszając tym samym efektywność wymiany ciepła, co może prowadzić do niebezpiecznego spadku temperatury wewnątrz komory fermentacyjnej. W pracy omówiono wpływ osadu na pracę wymiennika ciepła w biogazowni. W celu wyznaczenia współczynnika przenikania ciepła dla opływanego poprzecznie orurowania wymiennika przyjęto korelacje zaproponowane przez Churchilla i Bernsteina, natomiast wewnątrz orurowania wymiennika ciepła współczynnik przejmowania ciepła obliczono z korelacji Dittusa-Boeltera. Do obliczeń przyjęto zmierzone, rzeczywiste parametry pracy biogazowni. W pierwszym zagadnieniu wyznaczono zależność temperatury na powrocie z wymiennika ciepła oraz wydajności cieplnej wymiennika w zależności do grubości warstwy osadu i współczynnika przewodzenia ciepła osadu. Do obliczeń przyjęto stałą prędkość opływu orurowania substratem: 0.001 m/s oraz następujące współczynniki przewodzenia ciepła osadu: 0.3, 0.5 oraz 1.0 W/(mK). Wraz ze wzrostem grubości warstwy osadu na ściance wymiennika temperatura na powrocie z wymiennika rośnie, co prowadzi do obniżenia wydajności cieplnej wymiennika. W drugim zagadnieniu wyznaczono funkcję temperatury na powrocie z wymiennika ciepła i wydajności cieplnej w zależności od prędkości przepływu substratu w obrębie orurowania wymiennika ciepła oraz od grubości warstwy osadu. Do obliczeń przyjęto stały jednostkowy współczynnik przewodzenia ciepła osadu oraz orurowanie wymiennika bez osadu i z osadem o grubości warstwy osadu 0.005 m i 0.01 m. Wraz ze wzrostem prędkości przepływu temperatura na powrocie z wymiennika maleje, natomiast wydajność cieplna wymiennika rośnie. Orurowanie wymiennika ciepła jest zainstalowane blisko ściany komory fermentacyjnej, gdzie prędkości przepływu substratu są niewielkie. Wszystkie rezultaty obliczeń zostały przedstawione w formie wykresów. Jednym ze sposobów zwiększenia wydajności cieplnej wymiennika jest zwiększenie temperatury zasilania. Należy tu zaznaczyć, że zbyt duża temperatura w obrębie orurowania wymiennika może doprowadzić do zniszczenia mikroorganizmów w komorze fermentacyjnej. W pracy przedstawiono również pomiary zużycia energii na cele ogrzania komory fermentacyjnej w latach 2015-2017. Ilości zużytego ciepła na cele ogrzania komory fermentacyjnej rosła wraz z czasem eksploatacji komory fermentacyjnej w wyniku gromadzącego się na komorze fermentacyjnej osadu. Publikację uzupełniają zdjęcia przedstawiające osady na ścianach wymiennika ciepła.

Abstract

Biogas plants in Poland are currently one of the most profitable alternative energy sources. The high efficiency of the biogas plant is guaranteed first of all by the appropriate selection of heat exchangers inside the anaerobic digester. There is no data in the literature regarding the operation of heat exchangers used in an anaerobic digester. The sludge in the digester is often deposited on the tubes of the heat exchanger, thereby reducing the efficiency of the heat transfer which can lead to a dangerous temperature drop inside the digester. This paper discusses the influence of sludge on the operation of the heat exchanger in a biogas plant. In order to determine the heat transfer coefficient for the heat exchanger tubing flowing around, the correlations proposed by Churchill and Bernstein were adopted, while inside the heat exchanger tubing the heat transfer coefficient was calculated from the Dittus-Boelter correlation. The measured actual parameters of the biogas plant operation were used for the calculations. In the first issue, dependence of return temperature from the heat exchanger and thermal efficiency of the exchanger was determined depending on the thickness of the sludge layer and the thermal conductivity of the sludge. For the calculations a constant flow velocity of the substrate was assumed: 0.001 m/s and the following thermal conductivity of sludge were assumed: 0.3, 0.5 and 1,0 W/(mK). Along with the increase of the thickness of the sludge layer on the exchanger wall, the return temperature from the exchanger increases, which leads to a decrease in the thermal efficiency of the exchanger. In the second issue, the function of return temperature from the heat exchanger and thermal efficiency was determined depending on the substrate flow velocity and the thickness of the sludge layer. A constant unit thermal conductivity coefficient of the sludge and piping of the exchanger without sludge and sludge with the thickness of the sludge layer 0.005 m and 0.01 m were assumed for calculations. With the increase of the flow velocity, the return temperature from the exchanger decreases, while the thermal efficiency of the exchanger increases. The heat exchanger piping is installed close to the wall of the digester where the substrate flow rates are small. All calculation results are presented in the form of graphs. One of the ways to increase the thermal efficiency of the exchanger is to increase the supply temperature. It should be noted that too high temperature within the exchanger's piping can lead to the destruction of microorganisms in the fermentation chamber. The paper also presents measurements of energy consumption for heating the digester in 2015-2017. The amount of heat consumed to heat the fermentation chamber increased with the time of exploitation of the fermentation chamber as a result of the sludge accumulating on the fermentation chamber. The publication is supplemented with photographs showing deposits on the walls of the heat exchanger.

Słowa kluczowe:
beztlenowa komora fermentacyjna, wymiennik ciepła, osad

Keywords:
biogas anaerobic digester, heat exchanger, sludge