ARCHITECTURE CIVIL ENGINEERING ENVIRONMENT
The Silesian University of Technology No. 3/2016

THE USE OF HIGH MOISTURE SEWAGE SLUDGE IN THE CHP UNIT INTEGRATED WITH BIOMASS DRYING AND GASIFICATION

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Received: 6.06.2016; Revised: 20.06.2016; Accepted: 21.06.2016

Abstract
The paper presents the evaluation of the possibility of the use of a biomass with high moisture content in a cogeneration plant with gas piston engine. The dried sewage sludge-derived syngas is used as a fuel. Sewage sludge are characterized by about 70 wt% of moisture content after the dewatering process. The drying process which is applied as the next step requires great amount of energy. For this reason the thermal integration of the drying process with a piston engine which produce a significant amount of waste heat is proposed. The legal situation of the sewage sludge treatment is briefly explained. The thermodynamic analysis of the cogeneration plant based on the gas piston engine integrated with drying and gasification units was conducted. The models of individual components of the system were developed using Engineering Equation Solver and MS Excel software. The maximum moisture of the fuel acceptable for the autonomic operation of the plant is calculated. The influence of the plant's scale for the acceptable moisture content in the biomass is studied. The analyzes revealed, that the waste heat from the engine is not sufficient for the drying unit. The operation of cogeneration plant requires an additional source of energy or drying the sewage sludge in an independent installation to moisture content about 50-55%.

Streszczenie
W artykule przedstawiono ocenę możliwości zastosowania biomasy o wysokiej wilgotności w układzie kogeneracyjnym z gazowym silnikiem tłokowym. Paliwem wykorzystanym w układzie jest gaz powstały w procesie zgazowania osuszonych osadów ściekowych. Osady ściekowe cechują się wysoką zawartością wody, sięgającą 70% (masowo) po wstępnym odwodnieniu mechanicznym. Proces osuszania biomasy wymaga doprowadzenia znacznych ilości energii, dlatego zaproponowano integrację cieplną z silnikiem tłokowym, produkującym znaczne ilości ciepła odpadowego. Przedstawiono pokrótce akty prawne dotyczące utylizacji osadów ściekowych. Przeprowadzono analizę termodynamiczną układu kogeneracyjnego opartego o gazowy silnik tłokowy zintegrowany z instalacjami osuszania oraz zgazowania biomasy. Na potrzeby analizy opracowano modele poszczególnych komponentów układu wykorzystując programy Engineering Equation Solver oraz MS Excel. Wyznaczono maksymalną wilgotność paliwa dostarczanego do układu, dla której możliwa będzie autonomiczna praca instalacji. Przeanalizowano także wpływ wielkości instalacji na akceptowalną wilgotność paliwa. Przeprowadzone analizy wykazały, że ciepło odpadowe z silnika tłokowego nie pozwala na osuszenie osadów ściekowych w wymaganym stopniu. Praca układu kogeneracyjnego z silnikiem tłokowym możliwa jest przy zapewnieniu dodatkowego źródła energii lub przy wstępnym osuszeniu osadów ściekowych w niezależnej instalacji do zawartości wody na poziomie 50-55%.

Keywords: **Sewage sludge; Biomass gasification; Drying; Cogeneration.**

1. INTRODUCTION

The recognition of the importance of the correlation between the energetic efficiency and innovation of the power plants leads to distributed energy generation. Combined heat and power (CHP) production integrated with biomass as an energy source seems to be a reasonable solution for a number of issues. The CHP plants are characterized by a high operation reliability thanks to the use of well-known thermal processes and good thermodynamic characteristics. Cogeneration leads to high efficiency, reduction of environmental nuisance and provides economic characteristics favorable for the investors. The CHP plants are often installed close to the heat and electric energy consumers. They are also applied for production of energy directly for specific consumer, e.g., an industrial plant, a public utility, an airport or a commercial building [1, 2, 3]. The CHP plants may also be placed close to the fuel production facility e.g. the sewage treatment plant or the biogas plant, what is connected with the relatively small area required for the installation, especially if the modular building is used.

Gas piston engines are often used in the cogeneration systems. The biggest advantages of this solution is the low investment cost (comparing to other solutions) as well as the high efficiency in the wide range of load. The piston engines coupled with a generator are converting roughly 30-35% of chemical energy of the fuel to the electric energy. The remaining part (excluding unrecoverable losses) is converted into the high-temperature heat in exhaust gases and the low-temperature heat leaving the unit in a form of hot water produced in the cooling system and the intercooler. Low-temperature heat can make up to 50% of the heat production [4].

Sewage sludge is a waste which contains a great share of water what results in the utilization difficulties. The drying process is vital for the possible effective use of the sewage sludge. The first step is mechanical dehydration which results in the 25-30% of dry matter in the sludge [5, 6]. In the following stage thermal drying is performed, which requires a significant amount of heat to evaporate the remaining water. This stage is very energy-consuming or time-consuming (if the solar dryers are considered). Integration of the sewage sludge dryer with the gas piston engine, producing a great amount of the waste heat, seems to be a reasonable alternative.

Gasification is a thermo-chemical process of conversion of the solid fuel into a flammable gas. This process consists of the numerous chemical reactions of carbon with a gasifying agent (air, steam or mixture of these gases). The main components of the gas are: carbon monoxide, methane, hydrogen, carbon dioxide and nitrogen. The reactions occurring during this process may be distinguished between exo- and endothermic – which produce the heat and those which need the heat input, respectively. Possibilities of the use of gas from gasification process is widely analyzed in the literature [7, 8]. The main applications are: co-combustion in power boilers [9], the use as a reburning fuel [10, 11, 12] and a fuel for gas engines [4, 13].

2. SEWAGE SLUDGE MANAGEMENT

Waste Management Act [14] describes the municipal sewage sludge as the sludge, derived from sewage treatment plants, from the septic tanks or different sewage treatment installations with the composition similar to the composition of the municipal sewage sludge. According to the Waste Catalogue [15], the sewage sludge are classified as a waste with the code 19.08.05. Figure 1 presents the forecast of the sewage sludge production in the next few years, based on the National Waste Management Plan 2014 [16]. As can be seen in Fig. 1, the stream of produced sludge is constantly growing what is connected with the growing area with sewage system.

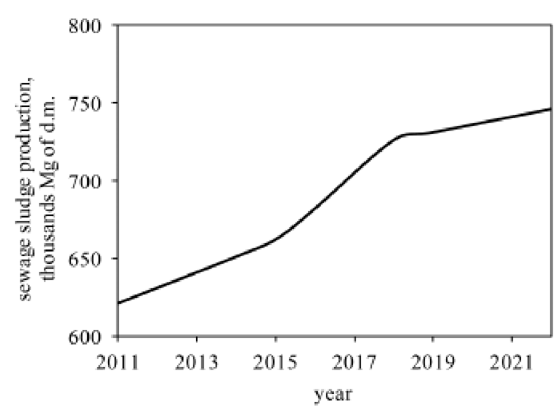

Figure 1.
The amount of sewage sludge production in Poland and estimated amount in the future [16]

Sewage sludge in Poland are mainly stored. This is a great concern, because of the currently applicable legal acts: Waste Management Act [14] as well as Ordinance of the Minister of Economy [17] and Ordinance of the Minister of Environment [18] which are the results of European directives [19, 20, 21]. The mentioned acts introduced the storage prohibi-

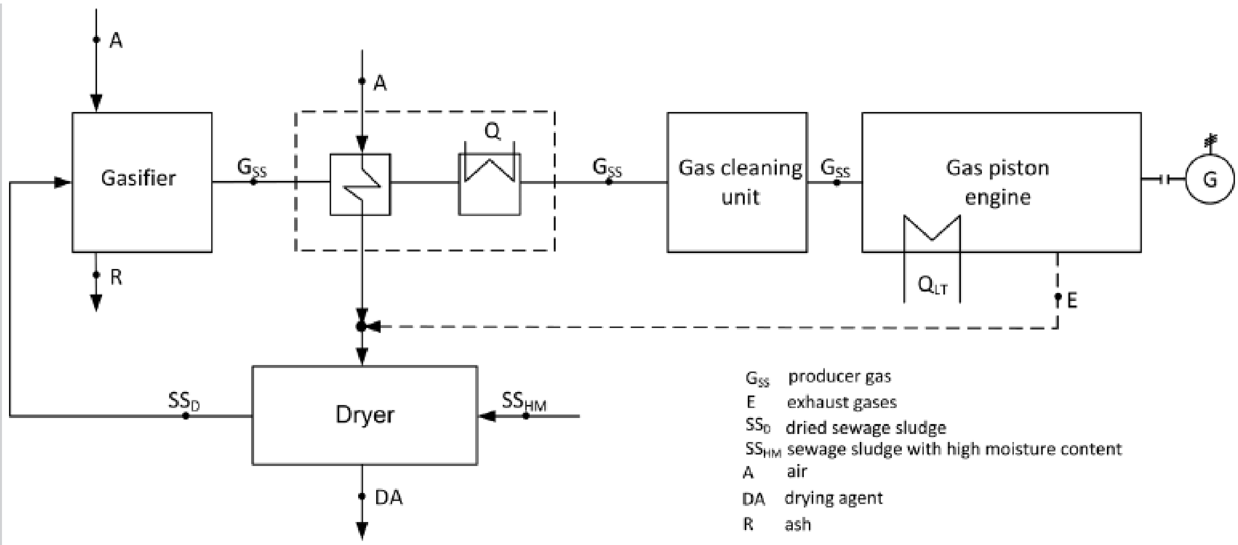

Figure 2.
The scheme of analyzed CHP unit

tion of the sewage sludge with the higher heating value equal or higher than 6 MJ/kg [22].

The development of the thermal methods of the sewage sludge utilization is planned [16]. The Waste Management Act [14] claims the thermal utilization of waste may be conducted by:

– direct combustion by oxidation,
– other processes of the thermal utilization including pyrolysis, gasification and the plasma process, where the occurring substances are subsequently used in the combustion process.

All the described legal aspects suggest that the development of the alternative for storage and combustion ways of the sewage sludge utilization is necessary. The gasification process seems to fit the legislator's expectations perfectly. The actual problems and development directions of sewage sludge management are widely described in [23].

3. AUTONOMIC CHP UNIT INTEGRATED WITH DRYING AND BIOMASS GASIFICATION – MODEL DESCRIPTION

The CHP unit is based on the gas piston engine fueled by gas produced from the sewage sludge in the integrated biomass gasifier. The unit was also integrated with biomass dryer. The integrated model of the unit was prepared using Microsoft Excel software with Visual Basic for Applications. The gasifier was modeled using Engineering Equation Solver, which was coupled with the integrated model using Dynamic Data Exchange protocol. Figure 2 presents the scheme of the analyzed CHP unit.

The gasifier was modeled using the simplified equilibrium model [24] based on two chemical reactions:

$$H_2O + CO \rightarrow CO_2 + H_2 \quad (1)$$

$$CO_4 + H_2O \rightarrow CO + H_2O \quad (2)$$

The equilibrium constant equations were combined with the molar balance equations for four elements (C, H, N, O). The temperature was assumed to be $T = 1000$ K, and the air excess ratio was equal to $\lambda = 0.4$.

Most manufacturers of gas piston engines for CHP systems do not provide detailed information about parameters of engines fueled with alternative fuels e.g. low-calorific value gases. Common way is to use the indicators describing the relative change in the engine parameters. For the purpose of the analysis, the indicators were adopted following [2] and defined by equations (3) and (4). The indicators are ratios of the parameter with alternative fuel to the parameter with nominal fuel.

The indicator of the relative change in the electricity generation efficiency was defined as:

$$c_\eta = \frac{\eta_{el}}{\eta_{el}^*} \quad (3)$$

The indicator of the relative change in exhaust gas temperature was defined as:

$$c_{T_{sp}} = \frac{T_{sp}}{T_{sp}^*} \quad (4)$$

The superscript "*" refers to the values of characteristics of the engine operating at nominal conditions.

For the calculations the following values of the indicators were assumed: $c_\eta = 0.909$, $c_{Tsp} = 0.979$ [2].

The database of the engines available on the Polish market (with electric power under 2200 kW) was created. The transition functions that allow to estimate the overall efficiency, electricity generation efficiency and the exhaust gas temperature as a function of nominal electric power were made. The model of calculation is described in detail in [4,25].

For the calculations of the drying process, the mixture of the exhaust gases and air as a drying agent was assumed. The following equations were used:

$$\dot{m}_{odp} = \dot{m}_p \cdot w - \frac{(1-w)\cdot \dot{m}_p \cdot w_s}{1-w_s} \quad (5)$$

where:

$\dot{m}_{odp}$ – mass flow of evaporated water during the drying process, kg/s

$\dot{m}_p$ – mass flow of the dehydrated sewage sludge, kg/s

w – moisture of the dehydrated sewage sludge, -

w_s – moisture of the dried sewage sludge, -

$$Q = w \cdot \dot{m}_p \cdot C_{p_w} \cdot (T_r - T_{0,ss}) + \quad (6)$$
$$+ (1-w) \cdot \dot{m}_p \cdot C_{p_{ss}} \cdot (T_r - T_{0,ss}) + \dot{m}_{odp} \cdot r$$

where:

Q – heat flow required in the drying process, kW

C_{p_w} – specific heat of water, kJ/kgK

$C_{p_{ss}}$ – specific heat of dry matter of sewage sludge, kJ/kgK

T_r – temperature of water evaporation, K

$T_{0,ss}$ – temperature of the dehydrated sewage sludge, K

r – enthalpy of water evaporation, kJ/kg.

The additional air is preheated using the produced gas. It was assumed, that the syngas leaves the gasifier at the temperature of 650°C and it has to be cooled down because of the restrictions of the gas cleaning unit. The two-stage cooler was proposed. In the first stage the ambient air was used as the cooling medium, which in the next step is mixed with the exhaust gases and used as a drying agent. The air mass flow depends on the assumed drying agent temperature at the dryer inlet. In the second stage of the cooler, the syngas is cooled using water to the temperature acceptable for the gas cleaning unit, which is assumed to equal 40°C. The temperature of the drying medium at the dryer outlet is assumed to be 105°C [5].

Cold gasification efficiency was assumed as follows:

$$\eta_{CGE} = \frac{\dot{E}_{ch_{LCVG}}}{\dot{E}_{ch_{ss}}} \quad (7)$$

where:

$\dot{E}_{ch_{LCVG}}$ – stream of chemical energy of gas obtained in the gasifier, kW

$\dot{E}_{ch_{ss}}$ – stream of chemical energy of dried sewage sludge, kW.

The analyses were made to calculate the maximum moisture content of the dehydrated sewage sludge which allows the CHP plant to operate as an independent unit. The influence of the drying agent temperature on the maximum moisture content was analyzed. The influence of the installation scale was also studied. The scale of the unit was presented as a change of the dry matter stream of the sewage sludge delivered to the gasifier in the range 0.05-0.4 kg/s, which describes the installation with the electric power of about 150-1300 kW. The composition of the sewage sludge is presented in Table 1. The sulfur content was ignored [26].

Table 1.
Ultimate molar composition of sewage sludge including the ash content (dry basis)

C	0.350
H	0.046
O	0.162
N	0.052
Ash	0.391

4. RESULTS AND DISCUSSION

The lower heating value as a function of the biomass moisture content for the analyzed sewage sludge is presented in Figure 3. Increase of the water fraction in the gasified fuel has a significant influence on the lower heating value of the produced gas – the LHV decreases, which corresponds with the results for similar equilibrium models, e.g. [26].

The maximum moisture of the dehydrated sewage sludge for different temperatures of the drying agent as well as the different target values of dried sewage sludge moisture after the drying process is presented in Figure 4. The higher temperature of the drying medium, the higher moisture is acceptable for the autonomic work, but it is also bounded with the fuel carbon loss. According to [2], the carbon loss at the drying agent temperature of 190°C equals about 1%

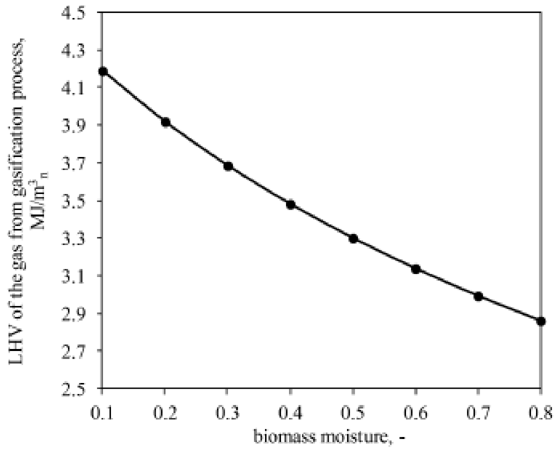

Figure 3.
The lower heating value of the gas obtained in the gasifier as a function of biomass moisture content

and it can be omitted in calculations. It should be noted, that increase of the maximum acceptable moisture is smaller with the growing temperature of the drying agent. A significant parameter is the expected moisture level of sewage sludge after the drying process. The range presented in Figure 4 is 10-30% because it is the range of moisture content in the fuel that may be used in the fixed bed reactor [2, 27].

Figure 5 presents the maximum moisture content of dehydrated sewage sludge as a function of the stream of dry matter of sewage sludge introduced into the gasification reactor in the range 0.05-0.4 kg/s which corresponds to the electric power of the gas piston engine in the range of approximately 150-1300 kW. The dependencies are presented for different levels of the moisture expected after the drying process. The temperature of the drying medium was 190 °C. The relatively small differences in the maximum moisture of dehydrated biomass in quite wide range of the engine electric power show that the selection of the optimal parameters will be able to be implemented in very different sewage treatment plants.

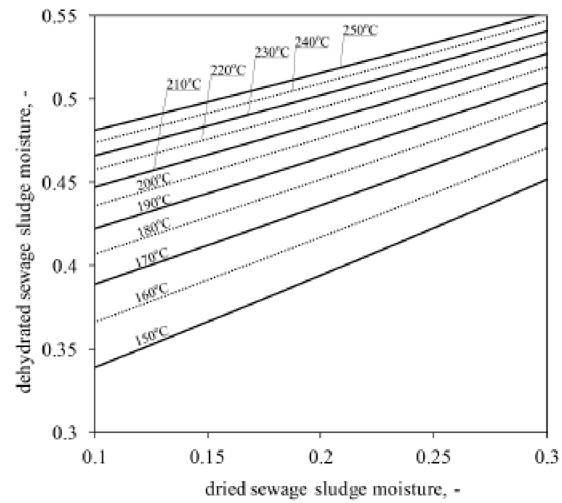

Figure 4.
Maximum moisture of dehydrated sewage sludge as a function of the expected moisture after drying process (for different temperatures of the drying agent)

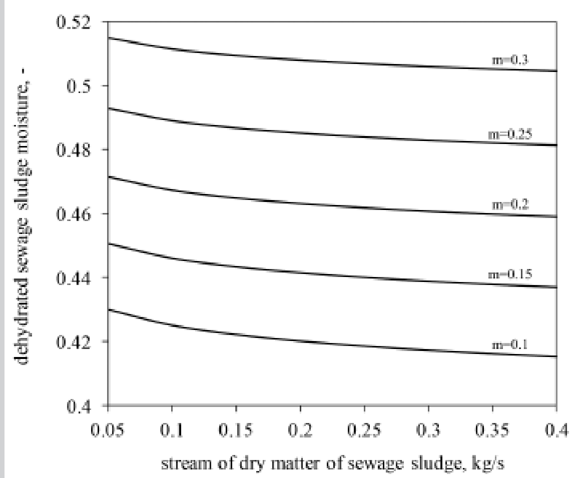

Figure 5.
The maximum moisture of dehydrated sewage sludge as a function of the stream of dry matter of sewage sludge (for different levels of the dried sludge moisture)

5. SUMMARY

The paper presents the thermodynamic analysis of the independent cogeneration installation fueled with sewage sludge of high moisture content. The fuel utilization is based on the gasification process and the system is oriented to electric energy production as well as the heat for the drying process. For the different (acceptable for the gasifier) moisture values of the dried biomass, the maximum input moisture of the dehydrated sewage sludge was calculated. The influence of the installation size was also studied. As mentioned earlier sewage sludge can be dehydrated to 70-75% of the moisture content. The calculations show that the amount of the heat produced in the analyzed system is not sufficient for its autonomic operation with the biomass with the high moisture content which can be obtained from the sewage treatment plant. For the presented structure maximal moisture content in dried biomass should not be higher than 50-55%, therefore the pre-drying of the biomass is necessary.

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