Thermal treatment of sewage sludge within a circular economy perspective: A Polish case study

S.Werle[1]
[1]Institute of Thermal Technology, Silesian University of Technology, Gliwice, 44-100, Poland
sebastian.werle@polsl.pl; phone: +48 32 237 2983; +48 32 237 2875

Abstract

Sewage sludge is a by-product of the wastewater treatment plant operation. Due to the fast urbanization and industrialization rate and the rapid growth of population, the world community has a serious challenge associated with its disposal. There is an urgent need to explore low cost, energy efficient and sustainable solutions for the treatment, management and future utilization of sewage sludge. Thermal conversion of sewage sludge (combustion and co-combustion, gasification and pyrolysis) appears to be most promising alternative for the management of sewage sludge according to a sustainable route. Among three main thermochemical processes it seems to be that gasification of sewage sludge has the most advantages. The aim of the paper is a presentation of the gasification process as a sustainable method of the management of the sewage sludge that takes into account the circular economy idea. The gaseous fuel production, phosphorus recovery potential and the solid adsorbent production during the gasification process is analyzed and discussed.

Keywords: circular economy, sewage sludge, thermal methods, Poland.

1. Introduction

Sewage sludge is a by-product of the wastewater treatment plant operation. Due to the fast urbanization and industrialization rate and the rapid growth of population, the world community has a serious challenge associated with its disposal. For the last 50 years, world population multiplied more rapidly than ever before, and more rapidly than it is projected to grow in the future. In 1950, the world had 2.5 billion people; and in 2005, the world had 6.5 billion people. By 2050, this number could rise to more than 9 billion and more than 11 billion in 2100 [1]. This material is a key issue in the majority of countries.

In the European Union (EU) the sewage sludge problem is being tackled by the general Directives and indicators and national legislative requirements.

The regulations concerning sewage sludge disposal

The European Union legislation concerning the disposal of sewage waste is included in the Council Directive 86/278/EEC on environmental protection of 12 June 1986 (the so-called Sludge Directive) [2].

The Directive 2000/60/EC of the European Parliament and Council of Europe adopted on 23 October 2000 sets of the norms of joint Community action in the field of Water Policy [3]. This Water Framework Directive (WFD) defines sludge not as a waste material, but as a ′product’ of sewage treatment. The operational directive of the WFD is the Directive 91/271/EEC adopted on 21 May 1991 concerning the treatment of municipal sewage [4]. The Directive obliges to monitor and report municipal sewage treatment and final disposal of municipal sewage sludge for agglomerations. Article 14 of this Directive refers to sludge produced in the course of sewage treatment and states that sewage sludge has to be reused in each appropriate case, to prevent adverse effect. Implementation of this Operational Directive till the end of 2015 increased the stream of sewage sludge, but on the other hand, it enabled other methods of sewage sludge reuse. Limits regarding storage of sewage sludge are introduced by the Directive 99/31/EC of 26 April 1999 on sludge storage, called the Landfill Directive [5].

Sewage sludge is the subject of European Parliament and Council Directive (2008)/98/EC of 19 November 2008 on waste [6] which is the Waste Framework Directive, that regulates recycling of wastes, including sewage sludge. According to the above mentioned Directive, sewage sludge defined as waste is a subject to the procedure assigned to waste treatment. The Directive states that prevention of waste production is the first priority, the next being preparation of waste for reuse, recycling, or other forms of recovery and final waste disposal. It is not possible to avoid the production of sewage sludge. Therefore, other steps of dealing with this specific waste are very important, i.e. preparation for reuse, understood as sludge reprocessing, including possible energy recovery in the Waste of Energy (WtE) way.

The concept of waste-to-energy has developed significantly over the last few decades. With initial developments in the 90′s, today′s waste-to-energy techniques have been greatly modernized as well as prioritized. The type of use feedstock has also been diversified. Sewage sludge is also recognized as a valuable feedstock for that purpose.

Thermochemical conversion of Sewage Sludge into Energy (StE) and fuel has been considered as one of the most attractive technologies to handle a growing amount of sewage sludge produced at the increasing number of sewage treatment facilities around the globe [7-11]. Thermochemical process offers not only massive volume reduction, but also effective pathogen destruction and potential for valorisation of energy-rich content [12]. In fact, via a proper technological strategy, valuable nutrients and metals can also be recovered [13-15].

Three main conventional paths of thermochemical conversion are pyrolysis, gasification and combustion.

Among this methods, it seems to be that gasification of sewage sludge has several advantages over a traditional combustion or co-combustion process and pyrolysis [16]. Gasification is the partial oxidation of biodegradable material in an air-restricted environment to yield a mix of flammable gases (H_2, CO, CH_4, etc., known as 'producer gas' or 'gasification gas') and a solid fraction of carbonaceous ash-rich char [17]. Producer can be used to generate mechanical or electrical power in dedicated gas engines or fed into the intake manifold of diesel engines in 'dual fuel' operation. Such gasification power systems are technologically mature, tolerant of diverse feedstocks and practical at smaller scales than combustion-based steam power systems [18]. Taking into consideration that gasification is the process characterizing by low level gasification agent environment, the volume of produced gas is lower in comparison of the volume of flue gas from the combustion process. Consequently, sulphur present in gasified material is transformed to H_2S, nitrogen to NH_3, chloride do HCl, the formation of dioxins, SO_2 and NO_x is prevented and gas cleaning installation is smaller and less expensive compared to classic combustion. This feature is very profitable taking into consideration the possible use such installation on the site of wastewater treatment plant. A more efficient scenario for sewage sludge gasification is combining the fuel production process with phosphorus recovery. After sewage sludge conversion, the residues are a sanitized source of mineral and some organic elements, including valuable fertilizing components, which makes them a potential substitute for natural phosphorus ore [19].

The development of gasification technology is associated with the development of gasifiers. Gasification reactors can be basically divided into 3 main types [20, 21]: fixed bed, fluidized bed and entrained bed gasifiers. One of the most widely known European plants using the gasification process is a system in Güssing (Austria), built in 2001, with power in the fuel of 8 MWth. Similar systems can be found, e.g., in Harbore (Denmark), Spiez (Switzerland), Kokemäki (Finland) or Skive (Denmark) [22].

During the sewage sludge gasification, the occurrence of the inorganic ant organic contamination including the waste by-products (ash and tar), is also important [23]. In that context, there are still new procedures are generated [24, 25]. For example, in sewage sludge and in tars from the gasification both toxic and hazardous organic substances (in sewage sludge: primarily of polycyclic aromatic hydrocarbons, in tars: phenols and their derivatives) and inorganic (e.g. identified nine different heavy metals) were identified. Moreover, in the ash mainly inorganic substances (heavy metals) were detected. The inorganic and organic contamination is mainly transported in the system: sewage sludge-gasification by-products. For them determination, basic instrumental methods (gas chromatography and absorption spectrometry) [24] can be used, but indirect methods like photoacoustic spectrometry and ecotoxicological analysis can be also used [25].

Gasification is valuable technology, which properly fit into the circular economy concept. The gasified sewage sudge is tranfomed into gasous fuel and valuable solid products which can be used as a adsorbent material and unconventional source of the phosphorus.

Sludge to energy in the Circular economy concept

The Circular economy (CE) concept was introduced by the British economists [26], but the best known definition is that put forward by the Ellen MacArthur Foundation [27]: "An industrial economy that is restorative or regenerative by intention and design".

Circular Economy (CE) package accepted by the European Union (EU) in December 2015 promotes close-loop flows of materials. The main targets provided in the documents refer to the prevention of waste landfilling, efficient use of resources and energy, as well as re-use waste and by-products. Sewage sludge - residue from Waste Water Treatment Plant (WWTP) - has a great potential and should be recycled in line with the CE strategy. As the circular economy is at the top of the EU agenda, all Member States of the EU should move away from the old-fashioned disposal of sewage sludge to a more intelligent waste treatment encompassing the circular economy approach in their policies.

The European Commission in its recently published communication, which is meant to clarify the role of WtE in the circular economy, expressed that: "Waste-to-energy processes can play a role in the transition to a circular economy provided that the EU waste hierarchy is used as a guiding principle and that choices made do not prevent higher levels of prevention, reuse and recycling." [28]. The concept of a circular economy has recently gained traction in European policymaking as a positive, solutions-based perspective for achieving economic development within increasing environmental constraints. Moreover, European countries increasingly indicate the circular economy as a political priority. Meeting the circular economy assumptions involves the need to introduce essential changes in all the EU member states, including Poland. The sewage sludge problem is a kay issue in that chalange.

2. Current Status of Sewage Sludge in Poland

The Republic of Poland is a central European nation located east of Germany on the geographical coordinates 52°N 20°E with a total land mass of 312,685 km^2. The land mass comprises 2.71% water and 97.3% land with 3,070 km^2 of territorial boundaries shared with Belarus, Czech Republic, Germany, Lithuania, Russia, Slovakia and Ukraine. The land terrain consists of flat plains and mountains along the borders in the south which account for its temperate climate. The seasonal weather is typically characterized by moderate to severely cold, cloudy winter conditions with regular rainfall whereas summer conditions are mild with periodic showers and thunderstorms.

According to year 2016 estimates, Poland is inhabited by 38.5 million people comprising 96.90% Polish, 1.10 % Silesian, 0.20% German, 0.10% Ukrainian, and others 1.70%. The economy of Poland is dominated by the Services sector with 55.60%, Industrial Manufacturing 41.10% and 3.30% Commercial Agriculture. The three sectors jointly account for USD$1.005 Trillion of Poland's Gross Domestic Product. Consequently, the per capita income of the average Pole is estimated at USD$26,000 which buttresses the nation's high living standards [29]. According to empirical studies, higher livings standards have significantly influenced the generation of municipal and industrial waste around the globe [30]. Similarly, Hoornweg et. al. [31] posit that rising urban population has increased solid waste generation by tenfold around the globe. In addition, global estimates indicate solid waste generation will double from 3.5 million to 6 million tons/day by 2025 exceeding environmental pollutants and greenhouse gases (GHGs) [31]. In corroboration Werle [32] assert that rising solid waste generation prompted by rising wealth and population dynamics will increase pressure on current waste management systems. In addition, this will result in significant socio-economic, environmental, technological and geopolitical implications globally.

Consequently, it stands to reason that sewage sludge production in Poland is set rise to 706 thousand Mg (dry matter) in the future [33]. Table 1 presents data on the disposal, management and utilization of the total industrial and municipal sewage sludge produced from over 4,255 waste water treatment plants (WWTP) operating in Poland for the year 2016.

Table 1. Sewage Sludge (SS) [in tonnes of dry solid] Production in Poland for 2016 (Statistical Yearbook of the Regions)

Sewage sludge (SS) utilization	Total SS (industrial and municipal)
Agriculture	133,887
Land reclamation	31,724
Compost production	32,807
Thermal conversion	194,677
Landfilling	97,569
Bulk storage	61,889
Other uses	394,638
Accumulated*	6,286,969

* Total annual SS accumulated on the WWTP on landfill areas

Analyzing the data presented in Table 1 it can be conluded that, SS is mostly utilized for agriculture, compost production, thermal conversion, bulk storage, and other uses than industrial SS.

The aim of the paper is presentation of the gasification process as a sustainable method of the management of the sewage sludge that takes into account the circular economy idea. The gaseous fuel production, phosphorus recovery potential and the solid adsorbent production during the gasification process is analyzed and discussed.

3. Gasification experiment

A fixed bed gasification facility located in the Laboratory of Fuels Combustion and Gasification, Institute of Thermal Technology of Silesian University of Technology, Gliwice, Poland was used for the current study. A schematic of the facility is shown in Figure 1.

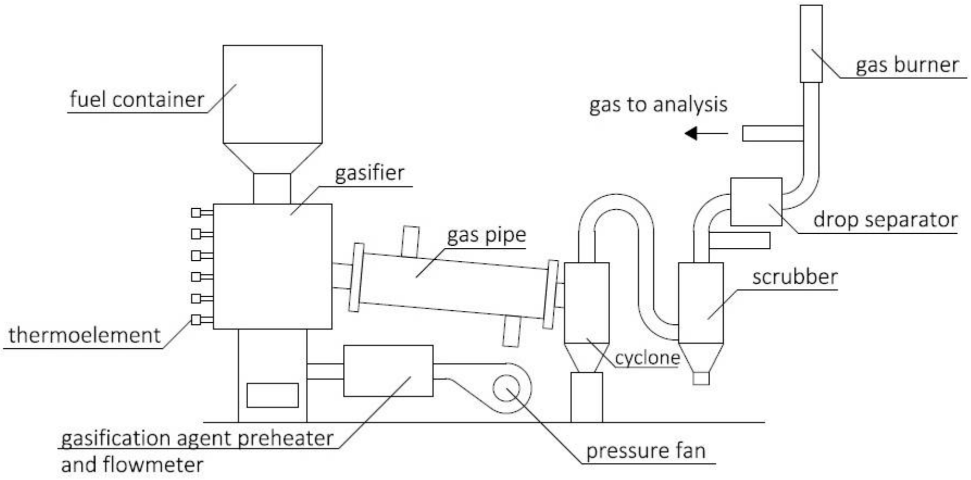

Figure 1 Schematic diagram of the experimental system [35]

The main part of the system was an insulated, stainless gasifier 150 mm internal diameter and the total height of 300 mm. The granular sewage sludge was fed into the reactor from the top located fuel container. The gasification air was fed from the bottom by the fan. The temperature inside the reactor was measured by six N-type thermoelements integrated with the Agilent temperature recording system. Thermocouples were located along the vertical axis of the reactor. Additionally, the temperature of the gasification gas at the outlet of the reactor was measured. The flow rate of gasification air and flow rate of produced gas was measured by flow meters. Gasification gas was transported by the gas pipe and then was cleaned by a cyclone, scrubber and drop separator. Volumetric fractions of the main components of produced gas were measured online using The Fisher Rosemount and ABB integrated set of analyzers.
Gasification methodology is presented in Table 2.

Table 2. Experimental matrix of gasification process

Sewage Sludge (SS)	Gasification agent	Air ratio λ, -	Tests
SS1 (from the mechanical-biological wastewater treatment plant) SS2 (from mechanical-biological-chemical wastewater treatment plant)	Ambient temperature atmospheric air	From 0.12 to 0.27	(i) Fuel production (ii) P recovery (fertilizer purposes) (iii) Sorbent production

In the gasification experiments, dried sewage sludge taken from a Polish wastewater treatment plant (WWTP) operating in the mechanical-biological-chemical and mechanical-biological-chemical system was used. After treatment, sewage sludge was stabilized by anaerobic digestion and dewatering. After it, sewage sludge was dried in cylindrical dryer with a heated shelf.

Ultimate and proximate analysis and occurrences of organic and inorganic contaminants

In the Table 3 the proximate and ultimate analysis of both analysed samples is presented. Following procedures and standards was used for the sewage sludge characterization. For the moisture PN-EN 14774-3:2010. The volatile content was determined according to standard PN-EN 15402:2011. The ash content was obtained using PN-EN 15403:2011. The calorific value was determined in accordance with standards CEN/TS15400:2006. The infrared spectroscopy analyzer was also used to carry out the ultimate analysis of the sewage sludge.

Table 3. Proximate and ultimate analysis of analysed samples (Werle and Dudziak, 2015)

Parameters	SS1	SS2
Proximate analysis, % (as received)		
Moisture	5.30	5.30
Volatile matter	44.20	36.50
Ash	49.00	51.50
Ultimate analysis, %dry solid		
C	27.72	31.79
H	3.81	4.36
O	3.59	4.88
N	13.53	15.27
S	1.81	1.67
F	0.003	0.013
Cl	0.033	0.022
LHV, MJ/kgdry solid	10.75	12.96

Gasification process results - influence of the air ratio on gas composition, LHV of gas and temperature distribution

The temperature distribution in the reactor was obtained by measuring the temperatures at six characteristic points of the reactor (Figure 2). The temperature measuring point of T_1 was measured at10 mm, T_2 at 60 mm, T_3 at 110 mm, T_4 at 160 mm, T_5 at 210 mm, T_6 at 260 mm above of the grate.

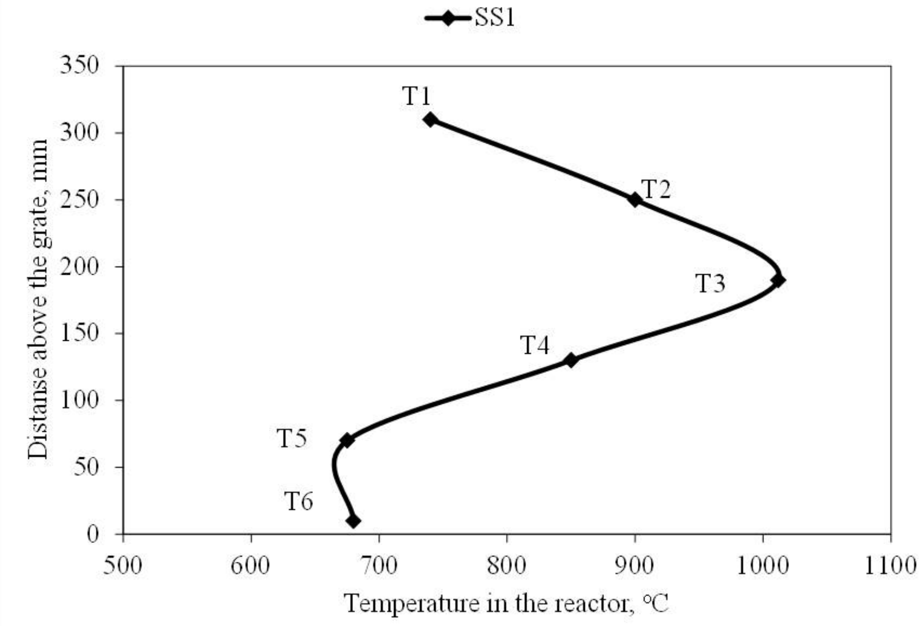

Figure 2 Temperature distribution in the reactor; SS1 gasification

Figure 2 showed that the temperature at T_3 point was always the highest, thus the temperature measuring point T_3 may be located in the partial oxidation zone, which should be the hottest area in the fixed bed gasifier. Correspondingly, the measuring point T_6 and T_5 may be located in the drying zone, T_4 in the pyrolysis zone, T_2 – oxidation (combustion) zone and T_1 – ash zone. Similar tendency was observed during the experiment with the SS2 sample.

In Figure 3 shows the evolution of the H_2, CO, CO_2 and CH_4 concentrations in gasification gas with varying air ratios for both analyzed sludge.

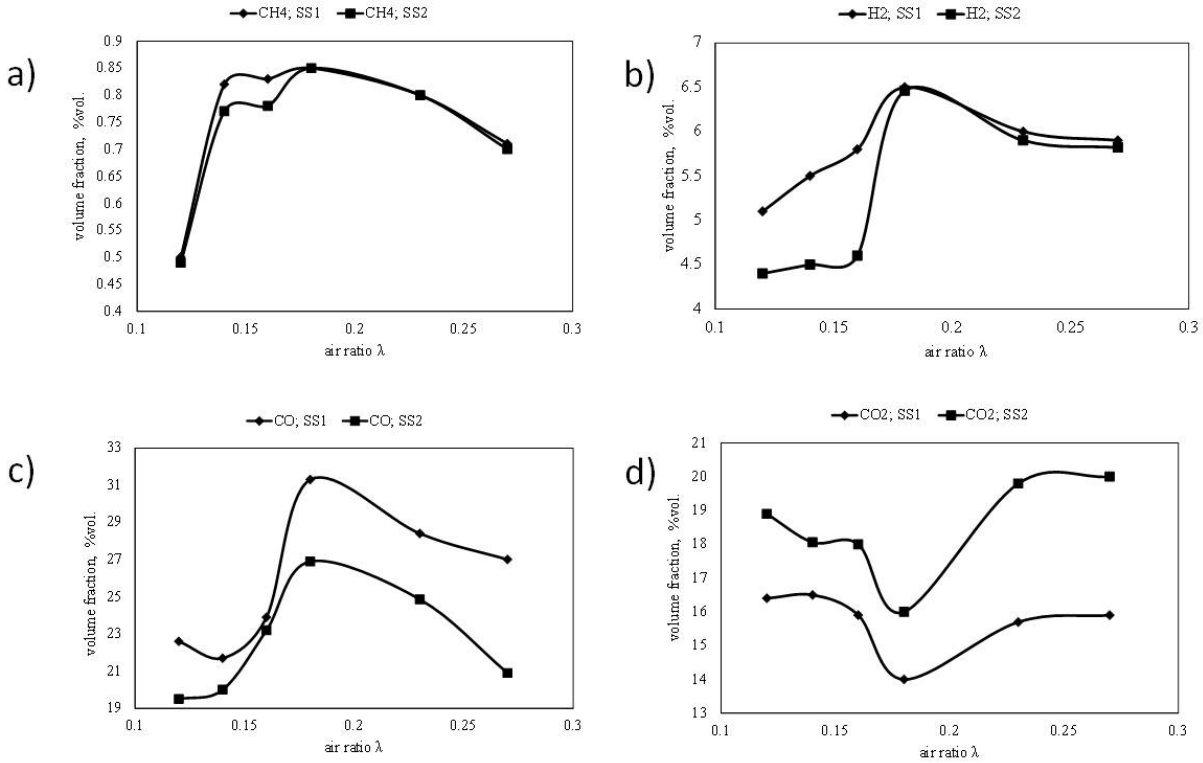

Figure 3 The volume fraction of main components in SS1 and SS2 gasification gas as a function of air ratio; a) methane; b) hydrogen, c) carbon monoxide, d) carbon dioxide

Analyzing this Figure it can be confirmed that throughout the range of analyzed air ratio volumetric fraction of main combustible components of gasification gas (CO and H_2) are higher in the case of the SS1 in comparison to SS2. At lower values of air ratio, CO fraction was found to be low and it starts to rise until the optimum air ratio of 0.18 and later drops for higher air ratios. The maximum CO average composition values of 31.3% for SS1 (and 26.9% for SS2) were obtained for gasification at λ=0.18. CO_2 shows an inverse relation with CO as the reactions that produce those gases are competing for the same reactants namely carbon. The concentration of carbon dioxide is generally expected to be minimum of the optimal air ratio range between 0.18-0.24. Rapid growth of CO observed in the value of the air ratio equal to 0.18 is caused by the dominant role of the primary water gas reaction. The reactions that can occur in the gasifier as a result of the gasification agent flow can be categorized as a the reaction of gasification agent and carbon in the fuel and the reaction of gasification agent and CO in the gas. The reaction of gasification air and carbon is an endothermic reaction that generates mainly CO whereas the reaction of gasification air and CO is an exothermic reaction that generates mainly CO_2 (and H_2). When gasification air is fed with the fuel into the reactor, the endothermic reaction of air and carbon occurs first (e.g. primary water gas reaction $CO+H_2O \rightarrow CO+H_2$), and the CO in a gaseous state produced from the fuel reacts with the residuals causing next reactions (e.g. water gas shift $CO+H_2O \leftrightarrow CO_2+H_2$). Thus, the composition of H_2, CO and CO_2 in the gasification gas changes according to the amount of the air supplied to the reactor.

In the Figure 4 there is presented dependence of the collated based on the volume fraction of the gas component lower heating value (LHV) of obtaining gas versus an air ratio.

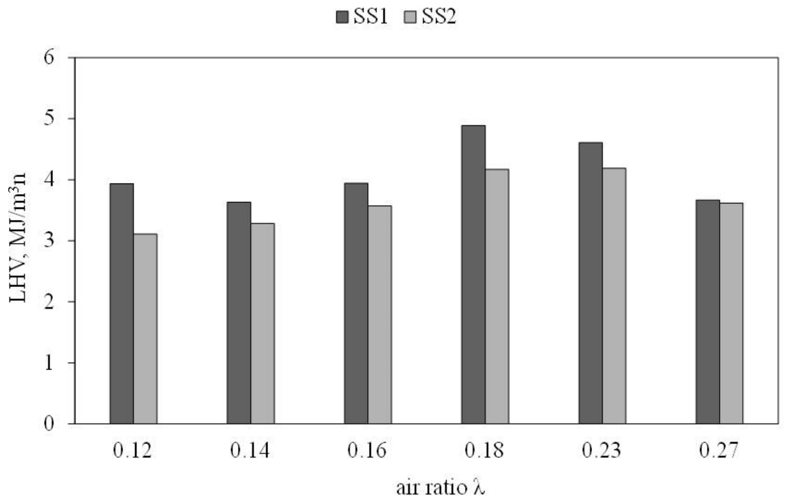

Figure 4 The Lower Heating Value of the SS1 and SS2 gasification gas as a function of the air ratio

The following formula was used [36]

$$LHV=0.126 \cdot CO+0.108 \cdot H_2+0.358 \cdot CH_4 \quad (1)$$

Analyzing this Figure, it can be concluded that taking into consideration the LHV of the gasification gas there is the optimum value of the air ratio equal to 0.18 in which the LHV takes its maximum value. It is true irrespective of the sewage sludge type. Above that optimal value, the thermo-chemical process could be shifted from gasification to combustion. Gasification process results shows that gasification gas is characterized by the lower heating value up to 5MJ/m^3_n (see Fig.5). This value is much lower than methane or hydrogen but is comparable with the LHV of the blast furnace gas. Gasification gas can be used to generate mechanical or electrical power in dedicated gas engines or fed into the intake manifold of diesel engines in 'dual fuel' operation. The chemistry purposes are also possible, eg. synthesis process.

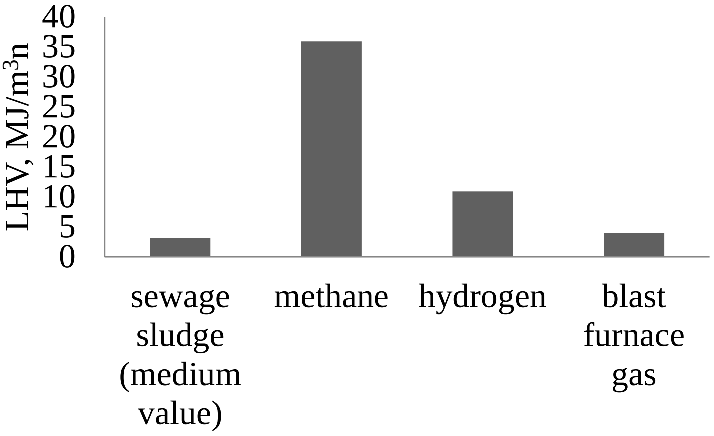

Figure 5 Lower heating value of sewage sludge gasification gas in comparison to other fuels

4. Management and purification of the gasification by-products

Adsorption

The process was carried out under static environment in Erlenmeyer flasks. A process temperature was 298K. To a solution of the adsorbate (V = 100 mL, pH = 7.0) at a concentration of 60 to 90 mg/L an adsorbent material (1000 mg/L) was added. The samples were shaken during 1 hour on a shaker produced by Labor System (Wroclaw, Poland) in a circular motion at a speed of 300 rev./min. Before marking the sample was filtered through a membrane with a pore size of 0.45 µm (Merck, Warsaw, Poland) to remove the adsorbent material. Equilibrium results can be analyzed using well known Freundlich adsorption isotherm. This way is a base for the design of the sorption process. In earlier work in this field, it was realized [37] that the degree of matching the theoretical Freundlich adsorption isotherm to experimental data is better than the Langmuir isotherm. This effect was especially strong in the studies of the phenol adsorption on ash from the SS gasification.

The Freundlich model is given as:

$$q_{\mathrm{eq}} = K_{\mathrm{f}} \cdot C_{\mathrm{eq}}^{1/n} \quad (2)$$

where:
q_{eq} – quantity of he adsorbed per specified amount of adsorbent (mg/g),
C_{eq} - equilibrium strength in solution (mg/L),
K_{f} and n - the Freundlich constants which are connected with the sorption intensity.

It is an empirical equation, based on sorption on a heterogeneous surface, which can be presented as a linear function. This form give possibility the constants K_{f} and n identification.

$$\log q_{\text{eq}} = \log K_{\text{f}} + \frac{1}{n} \log C_{\text{eq}} \quad (3)$$

It has been demonstrated that solid gasification by-products can be used a an adsorption material for elimination of toxic organic substances from the water streams, eg. phenol. Table 4 presents the comparison of the maximum adsorption capacity of the phenol monolayer on different adsorbents. Based on the presented data it can be concluded that the efficiency of phenol adsorption on the ash was greater than for the other unconventional adsorbents (bagasse fly ash, neutralized red mud, olive pomace). The adsorption of phenol was found for commercially available activated carbons and activated carbons derived from waste materials such as beet pulp or rice husk.

Table 4 Comparison of the maximum monolayer adsorption capacity of phenol onto various adsorbents

Adsorbents	q_{eq} (mg/g)
Activated carbon fibre	110.20
Beet pulp carbon	90.61
Commercial activated carbon	49.72
Rice husk carbon	22.00
Chemically modified green macro algae	20.00
Baggase fly ash	12.00-13.00
Neutralized red mud	5.13
Olive pomace	4.00-5.00
Sewage sludge (SS) ash	42.22

Phosphorus recovery potential

A more efficient scenario for sewage sludge gasification is combining the fuel production process with phosphorus recovery. Analysis shown that solid gasification residue is a valuable source of phosphorus compared to ashes after sewage sludge combustion, but its chemical properties as well as technological parameters differ from natural phosphate ore; therefore, such material should be well recognized and treated separately, with sewage sludge ashes or as an additive to standard raw materials. The solid gasification residue is a valuable source of phosphorus (20.06% P_2O_5) which is comparable to sewage sludge ash (22.47% P_2O_5). Its chemical properties as well as technological parameters differ from those of natural phosphate ore [20]. In contrary, micronutrients such as Fe (0.6-0.7%), Cu (0.0004-0.002%) Zn (0.049-0.52) and Mn (0.021-0.031%) essential for a proper plants growth are present in the extracts, which can be considered for production of fluid fertilizers applied to the soil for horticultural use in accordance to Regulation EC no 2003/2003.

Combining gasification process with nutrients recovery gives the opportunity for more environmentally efficient technology driven by sustainable development rules [19]

5. Conlcusions

The following conclusions can be formulated based on the performed studies and analysis of the obtained results:

- The operating conditions (amount of the gasification agent) of the sewage sludge gasification process greatly influence the gasification gas composition distribution.
- Higher values of the main components (especially C and H) in the sewage sludge plant affect the increase of the LHV of gasification gas.
- Taking into consideration the lower heating value LHV of the gasification gas there is the optimum value of the air ratio equal to 0.18 in which the LHV takes its maximum value.
- The yield of the main gasification gas components, CO, H_2 and CH_4, was enhanced by increasing the gasification agent temperature and increasing of the oxygen concentration in the gasification agent.
- Solid waste by-products from sewage sludge (ashes) can be used as an adsorbent for the elimination of toxic organic substances from water streams such as phenol. The sludge from sludge gasification should be subjected to deep purification processes.
- The gasification residue is a valuable source of phosphorus (20.06% P_2O_5) comparable to sewage sludge ash (22.47% P_2O_5) and Egyptian phosphate rocks (28.05% P_2O_5). chemical properties as well

as technological parameters differs from natural phosphate ore, therefore such material should be well recognized and treated separately.

- The results of the analysis indicate that there is a great potential for improvement in sludge management in the circular economy perspective.

References

[1] World Population Prospects 2017, https://esa.un.org/unpd/wpp/Download/Probabilistic/Population/
[2] Council Directive on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. Off. J. Eur. Commun., 181 (1986), pp. 0006-0012.
[3] Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. The joint text approved by the Conciliation Committee provided for in Article. 251.
[4] Council Directive 91/271/EEC concerning urban wastewater treatment OJ L. (1991), p. 135.
[5] Council Directive 99/31/EC of 26 April 1999 on the landfill of waste (Landfill Directive). Off. J. Eur. Communities L., 182 (1999), p. 16.
[6] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives (Waste framework directive, R1 formula in the footnote of attachment II).
[7] Chen, P, Xie, Q, Addy, M, Zhou, W, Liu, Y, Wang, Y, Cheng, Y, Li, K, Ruan, R.:Utilization of municipal solid and liquid wastes for bioenergy and bioproducts production. Bioresour Technol 215, 163–72 (2016).
[8] Ferrasse, JH, Seyssiecq, I, Roche, N.: Thermal gasification: a feasible solution for sewage sludge valorisation?. Chem Eng Technol. 26, 941–5 (2003).
[9] Samolada, MC, Zabaniotou, AA.: Comparative assessment of municipal sewage sludge incineration, gasification and pyrolysis for a sustainable sludge-to-energy management in Greece. Waste Manag. 34, 411–20 (2014).
[10] Rulkens, W.: Sewage sludge as a biomass resource for the production of energy: overview and assessment of the various options. Energy Fuels. 22, 9–15 (2008).
[11] Cao, Y, Pawłowski, A.: Life cycle assessment of two emerging sewage sludge-toenergy systems: evaluating energy and greenhouse gas emissions implications. Bioresour Technol. 127, 81–91 (2013).
[12] Jiang, L-b, Yuan, X-z, Li, H, Chen, X-h, Xiao, Z-h, Liang, J, Leng, L-j, Guo, Z, Zeng, Gm.: Co-pelletization of sewage sludge and biomass: thermogravimetric analysis and ash deposits. Fuel Proces Technol. 145, 109-115 (2016).
[13] Bridle, TR, Pritchard, D.: Energy and nutrient recovery from sewage sludge via pyrolysis. Water Sci Technol. 50, 169–75 (2004).
[14] Mulchandani, A, Westerhoff, P.: Recovery opportunities for metals and energy from sewage sludges. Bioresour Technol. 215, 215–26 (2016).
[15] Donatello, S, Cheeseman, CR.: Recycling and recovery routes for incinerated sewage sludge ash (ISSA): a review. Waste Manag. 33, 2328–40 (2013).
[16] Muzyka, R., Chrubasik, M., Stelmach, S., Sajdak, M.: Preliminary studies on the treatment of wastewater from biomass gasification. Waste Manage. 44, 135–146 (2015).
[17] Skorek-Osikowska, A., Uchman, W., Werle, S.: Modeling of energy crops gasification based on experimental data. ACEE Architecture Civil Engineering Environment. 10, 135–141 (2017).
[18] Pinto, F., Lopes, H., André, R.N., Dias, M., Gulyurtlu, I., Cabrita, I.: Effect of experimental conditions on gas quality and solids produced by sewage sludge co-gasification. 1. Sewage sludge mixed with coal. Energy and Fuels. 21, 2737–2745 (2007).
[19] Gorazda, K., Tarko, B., Werle, S., Wzorek, Z.: Sewage sludge as a fuel and raw material for phosphorus recovery: combined process of gasification and P extraction. Waste Manage. 73, 404-415 (2018).
[20] Gorazda, K., Tarko, B., Wzorek, Z., Kominko, H., Nowak, A.K., Kulczycka, J., Henclik, A., Smol, M.: Fertilizer production from ashes after sewage sludge combustion – A strategy towards sustainable development. Environmental Research. 154, 171–180 (2017).
[21] Werle, S.: Impact of feedstock properties and operating conditions on sewage sludge gasification in a fixed bed gasifier. Waste Manage Research. 32, 954–960 (2014).
[22] Uchman, W., Werle S.: The use of low-calorific value gases in environmental protection engineering. ACEE Architecture Civil Engineering Environment. 9, 127–132 (2016).
[23] Werle, S., Dudziak, M.: Analysis of organic and inorganic contaminants in dried sewage sludge and by-products of dried sewage sludge gasification. Energies 7, 462–476 (2014).
[24] Werle, S., Dudziak, M.: Evaluation of toxicity of sewage sludge and gasification waste-products. Przemysł Chemiczny. 92, 1350–1353 (2013).

[25] Werle, S., Dudziak, M., Grübel, K.: Indirect methods of dried sewage sludge contamination assessments. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering 51, 754–758 (2016).
[26] Pearce, D.W., Turner, R.K., Economics of natural resources and the environment, Johns Hopkins University Press, Baltimore 1989.
[27] Potocnik, J., Towards the Circular Economy – economic and business rationale for an accelerated transition, Ellen MacArthur Foundation, 2013.
[28] Communication from the commission to the european Parliament, the council, the european economic and social Committee and the committee of the regions The role of waste-to-energy in the circular economy, 2017.
[29] CIA World Factbook. Poland: Geography & Socio-Economic Status World Factbook: Country Profile 2016.
[30] Matsunaga, K, Themelis, NJ.: Effects of affluence and population density on waste generation and disposal of municipal solid wastes. Earth Engineering Center Report, 2002:1-28.
[31] Hoornweg, D, Bhada-Tata, P.: What a waste: a global review of solid waste management. Urban Development Series Knowledge Papers, 2012, World Bank Group, Washington DC, 1-98.
[32] Werle, S.: Sewage sludge-to-energy management in Eastern Europe: a Polish perspective, Ecol. Chem. Eng. S, 22, 459-469 (2015).
[33] Werle, S., Dudziak, M.: The assessment of sewage. sludge gasification by-products toxicity by ecotoxicologal test. Waste Management & Research 33, 696–703 (2015).
[34] Statistical Yearbook of the Regions – Poland: Central Statistical Office; 2016.
[35] Polish Patent, 2011. Biomass gasification installation, mainly for sewage sludge, Werle, S. and Wilk, R.K., No. P-397225, 2.12.2011.
[36] Kim, J.W., Mun, T.Y., Kim, J.O., Kim, J.S.: Air gasification of mixed plastic wastes using a two-stage gasifier for the production of producer gas with low tar and high caloric value. Fuel. 90, 2266–2272 (2011).
[37] Dudziak, M., Werle, S.: Studies on the adsorption of phenol on dried sewage sludge and solid gasification by-products, Desalination and Water Treatment. 57, 1067-1074 (2016).

Acknowledgments

The paper has been partially prepared within the frame of the Rector of the Silesian University of Technology Project (reg. number 08/060/RGJ17/011) and within the frame of the project Study on the solar pyrolysis process of the waste biomass financed by National Science Centre, Poland (reg. number 2016/23/B/ST8/02101).