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Investigation of sewage sludge treatment using air plasma assisted gasification

Nerijus Striūgas [a,*], Vitas Valinčius [b], Nerijus Pedišius [c], Robertas Poškas [d], Kęstutis Zakarauskas [a]

[a] Laboratory of Combustion Processes, Lithuanian Energy Institute, Breslaujos Str. 3, LT-44403 Kaunas, Lithuania
[b] Plasma Processing Laboratory, Lithuanian Energy Institute, Breslaujos Str. 3, LT-44403 Kaunas, Lithuania
[c] Laboratory of Heat Equipment Research and Testing, Lithuanian Energy Institute, Breslaujos Str. 3, LT-44403 Kaunas, Lithuania
[d] Nuclear Engineering Laboratory, Lithuanian Energy Institute, Breslaujos Str. 3, LT-44403 Kaunas, Lithuania

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ABSTRACT

This study presents an experimental investigation of downdraft gasification process coupled with a secondary thermal plasma reactor in order to perform experimental investigations of sewage sludge gasification, and compare process parameters running the system with and without the secondary thermal plasma reactor.

The experimental investigation were performed with non-pelletized mixture of dried sewage sludge and wood pellets. To estimate the process performance, the composition of the producer gas, tars, particle matter, producer gas and char yield were measured at the exit of the gasification and plasma reactor. The research revealed the distribution of selected metals and chlorine in the process products and examined a possible formation of hexachlorobenzene.

It determined that the plasma assisted processing of gaseous products changes the composition of the tars and the producer gas, mostly by destruction of hydrocarbon species, such as methane, acetylene, ethane or propane. Plasma processing of the producer gas reduces their calorific value but increases the gas yield and the total produced energy amount. The presented technology demonstrated capability both for applying to reduce the accumulation of the sewage sludge and production of substitute gas for drying of sewage sludge and electrical power.

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1. Introduction

In modern wastewater treatment plants (WWTP) a large amounts of sewage sludge is produced. With the expansion of its infrastructure, the amount of sewage sludge is increasing proportionally. In most WWTPs for stabilization and recovering of energy from sludge, the anaerobic digestion process is used first (Fabregat et al., 2015). Further disposal of dewatered digestate waste can be followed by different processes, ranging from composting and use in agriculture to incineration or thermal treatment for energy recovery. The experience of European countries show that the most reasonable utilization of the sewage sludge is energy production (Kelessidis and Stasinakis, 2012). Since the sewage sludge is an organic matter in most part that produces heat when combusted, utilization of the sewage sludge for energy production is considered to be the most prospective use (Fonts et al., 2012).

Incineration still is the mostly used thermal treatment method for sludge (Samolada and Zabaniotou, 2014). In order to utilize the digested sewage sludge, it is advisable to properly preprocess it, i.e., to dry out and pelletize or to produce briquettes. In other cases, mono-combustion is complicated and additional fuel is required to efficiently sustain combustion (Lin and Ma, 2012). Besides, the current sludge combustion is still a relatively expensive technology and is cost-efficient only for utilization of large quantities of obtained sludge. Centralized WWTPs in small countries like Lithuania produce relatively small amounts of sewage sludge. The annual amount of dry sewage sludge produced in Lithuania is up to 50 thousand tons of dry material. The largest wastewater treatment plant operated in Lithuania, located in Vilnius (population ~530 thousand), produces approximately 22 thousand tons of dried sewage sludge per year, but in other towns with less population this amount is in the range of 1–6 thousand tons. This amount is similar to the European average of 90 g dry weight per person per day (Fytili and Zabaniotou, 2008). Because of relatively low amount of sewage, the power output of the heat generators combusting the dry sewage sludge would be low as well, e.g.,

* Corresponding author.
E-mail address: Nerijus.Striugas@lei.lt (N. Striūgas).

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~10 MW in Vilnius or from 0.5 to 3 MW in other towns. Therefore, construction of low-capacity sludge incineration plants complying with all the environmental requirements for emissions would be economically ungrounded.

Dried sewage sludge is classified as a non-hazardous waste that can be stored or transported without special strict requirements. However, for the energy production by incineration of dried sludge, EU Directive 2000/76/EC (Directive 2010/75/EU) and other relevant documents apply (Manara and Zabaniotou, 2012). To conform to these regulations, the standard combustion facilities cannot be used for incineration of sewage sludge. According to above directive requirements, an incineration plant must be designed, constructed, installed and operated in such a way that during the process, even at the most unfavorable condition, the temperature of the emitted gas after the last air injection remains 850 °C for at least 2 s continuously at the internal wall of the combustion chamber or at any other typical measurement point. However, besides the incineration technology, other perspective alternative ways of thermochemical utilization of dried sewage sludge exist: pyrolysis (Fonts et al., 2012; Cao and Pawłowski, 2012), gasification (Speidel et al., 2015) or a less developed supercritical water oxidation (Zhang et al., 2010; Molino et al., 2016). Pyrolysis is predominantly meant for extraction of liquid chemical species, whereas the other two – for gaseous products. As the supercritical water gasification remains in the development stage, traditional gasification process would be the most rational of all the mentioned alternatives. Gasification is applied to extract from the sludge a valuable product – combustible gas that can be used to produce electricity and heat needed for sludge drying.

The downdraft gasification is attractive for small scale processing of various types of biomass, including waste (Striūgas et al., 2014). Additionally, in the downdraft gasification process the amount of tars is less than that in other common gasification technologies such as updraft or fluidized bed. However, the waste materials like sewage sludge contain high amount of ash with low softening temperature and it is rather obvious that the high temperatures must be avoided due to possible formation of agglomerates (Ong et al., 2015; Li et al., 2016). On the other side, as the gasification temperature decreases, the concentration of condensable tars and other uncracked compounds in the producer gas increases. There are many ways to produce clean gas at the exit from the gasifier (Prabhansu et al., 2015), but plasma processing is considered the most promising technology for clean energy production from waste (Mountouris et al., 2008). Additionally, the life cycle assessment shows that two-stage gasification-plasma process has lower environmental impact among other advanced thermochemical processes (Evangelisti et al., 2015). Due to high temperature and followed rapid quenching of the products, the thermal plasma gasification allows to minimize the possibility of forming toxic compounds during treatment of waste (Gomez et al., 2009). As an example, destruction and removal efficiency of chlorinated organic compounds by means of plasma gasification was explored in work of (Safa and Soucy, 2014). According to authors, thermally decomposing contaminated liquids containing PCBs and dioxins, the destruction efficiency of hazardous substances reaches up to 99.99999% and the emission level of toxic compounds like dioxin and furan were below the limits indicated in the strictest world standards. (Cheng et al., 2015) performed experimental investigation on the thermal plasma pyrolysis of the coal tars showing that process can be useful to transform hydrocarbons into more valuable gaseous products containing mainly H_2 and CO.

The one-step plasma processing of various waste is widely applied worldwide (Fabry et al., 2013; Li et al., 2016). Whereas the two-step system combining conventional gasification and stage of syngas processing with plasma has a quite different approach (Morrin et al., 2012). The first step is used to transform low-grade biomass or waste while second to crack tars or other contaminants, in order to avoid formation of toxic compound and increase conversion efficiency. In the works of (Materazzi et al., 2014, 2015) plasma processing of raw gas obtained during gasification of different waste was applied. Authors revealed the potential of thermal plasma technology to almost completely crack tars into simple gaseous products H_2 and CO, reform organic sulphur compounds and additionally increase the calorific value of the cleaned producer gas. The high consumption of electrical energy is the main drawback of thermal plasma. However, the thermodynamic analysis of two stage plasma assisted waste gasification process performed by Materazzi et al. (2016) shows that energy efficiency using a plasma converter is greater than that in case of ordinary thermal cracker.

According to literature review it is evident that thermal plasma processing of biomass and various waste is effective and perspective tool for energy recovery. Currently, the conversion technology of solid waste using plasma for energy recovery is still in its infancy. There is a lack of information on the process performance of two-stage plasma assisted gasification using sewage sludge as a feedstock. In this study, the downdraft gasification unit was adopted for treatment of dried sewage sludge in order to produce clean producer gas for substitution of natural gas used for drying of mechanically dewatered digested sludge. For producer gas cleaning and abatement of toxic compounds, the thermal plasma reactor was introduced. Therefore, the objective of this work was to perform experimental investigations of sewage sludge gasification, and compare process parameters running the system with and without the secondary thermal plasma reactor.

2. Material and methods

2.1. Dried sewage sludge characteristics

Sewage sludge is a complex feedstock for both mono incineration and gasification. The earlier investigation (Striūgas et al., 2014) has shown that the pelletization of fine feedstock is crucial for the feeding it to the gasification reactor. During the gasification of pelletized sludge, pieces of solid char (consisting of metal and char compound) whose gasification is especially complicated in the further zones of the reactor are produced. Besides, these pieces are prone to block the moving parts of the reactor and/or to affect them mechanically. In contrast, non-pelletized mixture of dried sewage sludge and wood pellets is thermally broken down more evenly and the appearing coke particles are more fragile and easier to remove from the gasification reactor.

Having determined that pelletized mixture of dried sewage sludge and sawdust is difficult to gasify, in this work, experiments were performed with non-pelletized mixture of dried sewage sludge and wood pellets at the ratio of 30 and −70 wt.%, respectively. The anaerobically digested and thermally dried sewage sludge was acquired from a local WWTP in the form of irregularly shaped round granulates, while soft wood pellets from local producer. The proximate and ultimate analysis, shape and size of the feedstock are presented in Table 1. Feedstock analyses were performed using an IKA C5000 calorimeter, a Flash 2000 CHNS analyzer, DIONEX ISC-5000 Ion chromatograph, ICP-OES Optima 8000 spectrometer and a NETZSCH STA 449 F3 Jupiter thermogravimeter.

2.2. Experimental setup

The main components of the experimental setup are the gasification reactor, the plasma reactor, the gas cooler, the electrostatic

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