Sustainable utilization of the sewage sludge using combined drying, torrefaction and plasma gasification technologies

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Abstract. This paper presents complete mass and energy balance of a novel installation for thermal utilization of the sewage sludge. Calculations were performed for the typical output of a wastewater processing plant in a middle size Polish town. Overall, the proposed configuration seems to be advantageous, as the proposed installation is fully sustainable and does not need external energy sources, due to maximized heat recovery from many different sources. Optimization of the heat use is performed, by utilizing all the available heat sources, including low-quality heat, such as the latent heat of water vapors, present in wet air after drying. Despite using plasma gasification system, the installation is able to generate surplus electricity, which can be used as a power source for all of the auxiliary devices, such as fans, augers and PLC systems. The proposed system can be implemented in the water treatment plants, in towns with the total amount of inhabitants ranging from a couple of thousand up to 40 thousand. System does not require anaerobic digestion of the sewage sludge. Nonetheless, the use of anaerobic digestion brings some advantages as the producer gas from the gasification installation can be mixed with biogas.

1. Introduction

Sewage sludge comes from the wastewater treatment and is a residue which is becoming increasingly problematic. It consists of water, organic matter, including dead and alive pathogens, as well as organic and inorganic contaminants such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals [1,2]. The risk of sewage sludge being biologically active is something, that needs to be taken into the account during its utilization. Due to this reason, a lot of work has been undertaken so far regarding deactivation and stabilization of the sewage sludge [3–8].

Due to various environmental and health and safety concerns, sewage sludge is a subject of various regulations both on European Union (EU) and on National levels. In the case of national levels, some national regulations are more strict in comparison to the requirements set by EU regulations [9–11]. Utilization varies, among different EU countries, as depicted in figure 1. It is clear, from the figure 1, which is based on the official statics from Eurostat [12], that Germany produces the biggest amounts of the sewage sludge in Europe and also is a leader in thermal utilization, whereas the UK dominates in terms of the use of the sewage sludge in agriculture.
Following regulations are important on EU level [10,11]:

- Water Framework Directive 2000/60/EC on water protection: The aim of this directive is a long term reduction of contaminant discharges into the aquatic environment.
- Directive 91/271/EEC on urban wastewater treatment: The directive aims to prevent harmful effects on soil, vegetation, animals and man.
- Directive 96/61/EC concerning integrated pollution prevention and control,
- Directive 99/31/EC on the Landfill of Waste
- Directive 86/278/EEC on the use of sludge in agriculture

According to Polish law landfilling has been banned since the 1st of January 2016 [13]. Regulation of the Polish Minister of Economy from 16th of July 2015 states that it is not allowed to landfill stabilized sewage sludge (waste code number 19 08 05) with a heating value exceeding 6 MJ/kg [6]. Moreover, in case of Poland, also new Renewable Energy Act is significant, as it gives a legal framework for sewage sludge to be considered biomass, which in turn allows thermal utilization installations to reap benefits of the support, given to renewable energy sources [14].

Thermal utilization of sewage sludge in Poland used to be relatively expensive, typically between 550 PLN/ton\(_{dry}\) and 900 PLN/ton\(_{dry}\), mainly due to the price of energy carriers [15]. Nowadays, in Poland there are at least 11 facilities, dedicated to incineration of the sewage sludge, mostly using the fluidized bed, and sometimes moving grate, combustion systems [2,15,16]. Moreover, cement
production plants (13 in Poland) [17], as well as municipal waste incineration plants (at least 17 in Poland) [18,19], are viable utilization options, for as long as transportation cost is not significant (in the close vicinity). Therefore sewage sludge utilization problem, in Poland, is the most pressing matter for small and medium-size towns, which produce too much sewage sludge to make agricultural use in the close vicinity a viable option.

2. Novel thermal utilization methods, viable for sewage sludge

Torrefaction is a promising thermal valorization technique, that allows upgrading of low-quality solid biofuels and turns them into a marketable commodity, that in its properties resembles coal [20]. Process of thermal valorization of the fuel, called torrefaction, is performed under ambient pressure and at temperatures ranging between 250°C to 300°C [20–22]. Products consist of torrefied biomass (sometimes called a bio-coal), CO, CO₂, small amounts of hydrogen and methane, as well as a multitude of volatile organic compounds, some of them condensing in ambient conditions [20,23,24]. Depending on the initial moisture content, at the inlet to the torrefaction reactor, water vapour content of torgas can be substantial. Moreover, as many of the reactor types use flue gases, oxygen might also be present in torgas. It can also be present in indirectly heated reactors, if the integrity and tightness are lost, due to leakage. However, this can happen only if the pressure in the burning chamber is significantly lower than ambient. The influence of the presence of oxygen (close to 0% up to 15% ) on torrefaction of various types of biomass was reported by many studies [25–31]. Presence of both vapours and oxygen can have a significant influence on the products of the torrefaction of sewage sludge, as demonstrated by Pawlak-Kruczek, et al. [32]. Moreover, the use of additives during the torrefaction of the sewage sludge, for improvement of the properties of torgas was also a subject of investigation [33]. Some works suggest torrefaction as a technique to improve subsequent gasification of biomass [34]. Fundamental work, laying foundations for thermal treatment of sewage sludge has been performed, using TGA (Thermo-Gravimetric Analysis) and DTG (Differential Thermo-Gravimetric) techniques [35–37]. In terms of the properties of biocoal, an increase of the higher heating value (HHV) of the pretreated sewage sludge, in comparison to the feedstock, was observed in some studies [38–40]. Increase in ash content is also reported [38,39].

An influence of carbonization on the environment is generally considered positive [36,41,42]. Some work was performed also on torrefaction of the sewage sludge in laboratory-scale reactors, such as fluidized bed reactor and auger reactor [43,44]. A decrease in the energy density, on a dry basis, was observed for both of the reactors. Some mass and energy balances, for installations using a torrefaction module, have been published for different sewage sludge utilization plants. One such example is a hypothetical plant, envisioned by T.X.Do et al., that used fry-drying, torrefaction and steam boiler [45]. The boiler used a part of the product for supplying its energy needs, thus allowing full self-sufficiency of the plant, with an additional output of 33% of the dry solid mass, originally fed to the dryer [45]. Peckyte and Baltrenaite studied the properties of carbonized products, obtained from residues of various types of the sludges from paper and leather industries, and determined that produced biochars restrained leaching of heavy metals [46].

Gasification is a process that converts solid fuel into combustible gas, which has been a subject of extensive research for various materials of biological origin. Gasification of sewage sludge has been a subject of intensive investigation. Decreasing temperature and increasing concentration of combustible components of the producer gas has been observed by Werle, with an increasing oxygen content of the sludge [47]. Some studies reported relatively high hydrogen content, exceeding 40%, for fluidized bed gasification of sewage sludge in a lab-scale gasifier [48]. Values for fixed-bed gasification were somewhat lower, nonetheless, exceeding 30% [49]. The yield of combustible compounds, during gasification of sewage sludge, can be increased by increased air temperature, at the inlet of a fixed bed gasifier [50]. In his work on combustion of the producer gas from sewage sludge, Werle determined that the laminar flame speed increased with increasing hydrogen content [51]. Some studies have proven the possibility of using the producer gas, from sewage sludge gasification, in spark-ignition engines.
[52]. Nonetheless, producer gas from sewage sludge requires 40% addition of methane to obtain a satisfactory performance of a spark-ignition engine, according to Szwaja et al. [53].

Tars from gasification of sewage sludge, according to Werle and Dudziak, in vast majority consist of phenols and their derivatives [54]. Reed et al. determined that condensed phase of the producer gas, from gasification of sewage sludge, may consist of various species containing Ca, ammonium chloride (NH₄Cl), as well as various species containing barium, mercury and zinc [55]. The study of Pawlak-Kruczek et al. proposed anticipating the possible severity of the tar deposition problems in gas coolers, by using a tar deposition diagram [56]. The study showed, using this diagram, that severe torrefaction of sewage sludge, prior to the steam gasification, results in a decrease of the content of tars with a melting point higher than 40°C [56].

Information, presented in the literature, on commercial gasification installations, dedicated to sewage sludge, is very limited. A case study on the commercial-scale gasification of sewage sludge was performed for the Greek island of Psittalia, using GasifEq equilibrium model, was performed by Montouris et al. [57]. It determined, that plasma gasification of sewage sludge from, can lead to net production of electricity [57]. The calculation, performed for a hypothetical installation, assuming the processing of 250 ton/day (moisture content of 68%), has shown the possibility to supply electric power of 2.85 MW [57]. Some research groups conducted successful experiments with a two-step plasma processing units [58,59], demonstrating on a laboratory scale, the overall feasibility of the concept, along with the possibility of the reduction the tar content down to 90 mg/m³ [59].

3. The novel technology, for sustainable and cost-effective thermal utilization of sewage sludge

In order to achieve full sustainability, technology should be able to supply its own energy requirements, both in terms of the necessary amounts of energy as well as its quality and final form. i.e. no matter how much heat is being produced, it does not seem to state that installation is fully sustainable if it produces a surplus of heat and in the same time needs an external energy source (grid or fossil fuel) to supply its own electricity needs.

A complete PFD (Process Flow Diagram) of such an installation is depicted in figure 2. This solution uses proven tape drying technology that utilizes a couple of different sources of heat:

- The heat from the cooling of the engine (due to the space limitation of the diagram intermediate heat exchangers are omitted in figure 2)
- A part of the physical enthalpy of the exhaust gases (due to the space limitation of the diagram intermediate heat exchangers are omitted in figure 2)
- A part of the physical enthalpy of the producer gas, recovered during the gas purification stage (due to the space limitation of the diagram intermediate heat exchangers are omitted in figure 2)
- A part of the latent heat of water vapors in the wet air, after drying

The balance, presented in the figure , does not take into account the electricity requirement for the auxiliary devices, such as fans and augers. Recalculation of a part of the stream of the drying agent is utilized in the proposed installation by the dryer, in order to obtain velocities, necessary to achieve the optimum drying rate at a relatively low temperature of the drying agent.

Mass yield ($Y_m$) and energy yield ($Y_e$) were used in calculations of mass and energy balance for torrefaction module since they are typical performance indicators for the torrefaction process [20,33,60,61].

$$Y_m = \frac{Q_{m_{feedstock}}}{Q_{m_{product}}}$$ (1)

The energy yield was calculated using the well-established formula [20,38,62]:

$$Y_e = Y_m \cdot \frac{HHV_{feedstock}}{HHV_{product}}$$ (2)
The research group of Boilers, Combustion and Thermal Processes at Wroclaw University of Science and Technology, has developed and patented a flexible, multi-stage tape reactor (Figure 3). This device depending on the temperature regime can easily perform the duties of the dryer and/or torrefaction reactor. Successful trials of the torrefaction of sewage sludge, as well as various other types of biomass, have been performed in recent years [56,60,63]. Patented technology, presented in figure 3, uses external heating of the processed material, through the surface of metal plates. The feedstock is being fed from the hopper to the reactor by a chain conveyor. On both ends of the reactor, airlocks are being used to prevent the escape of torgas. The product is being cooled down in a screw conveyor with a water jacket, at the bottom of the installation. Torgas is being burned in the combustion chamber, located beside the torrefier. An oil burner is used as a source of startup heat and as a pilot flame source during normal operation. When working in torrefaction mode, installation is operating reasonably close to the autothermal point, whereas the supply of auxiliary heat is determined by the moisture content of the feedstock. The main advantage of this technology is the fact that processed material is touching only hot surfaces of the reactor, thus significantly reducing the risk of the agglomeration of the particles, due to sticky tars condensing on the surfaces. This has the potential to reduce the operational cost, by reducing the risk of emergency shutdowns due to clogging. Residence time is controlled by the velocity of the chains along the length of the reactor, with the scrapers attached to them.

The assumed average temperature of the hot air, delivered under the top plates during the torrefaction of pre-dried sewage sludge, was assumed to be 320°C, for the energy balance calculations performed within the scope of this study. This was an arithmetic average and the calculation was based on the values measured by three thermocouples installed inside of each of the shelves, close to the middle of respective top plates (Tp2, Tp7 and Tp8 – see Fig.3). The average total residence time of 40 minutes, which was necessary to assume certain mass and energy yield for mass and energy balance calculations.
Mass and energy yields, obtained during the experiments of torrefaction of pre-dried sewage sludge in this installation, were used for heat and energy balance calculations.

Figure 3. Multistage tape dryer/torrefier developed by Wroclaw University of Science and Technology (Tp—thermocouple; TgS—Torgas sampling port; FgS—Flue gas sampling port; WP—Preheated secondary air blower; WM—Primary air blower; WS—Flue gas extraction fan; SC1—airlock at the inlet; SC2—airlock at the outlet; PR—pressure regulator; PP—oil burner; P—pressure gauge; A,B,C – ducts delivering hot flue gases to the inside of the shelves; D,E,F – ducts for evacuation of the flue gases out of the shelves; G – main flue gas extraction duct; H – flue gas recirculation to the freeboard of the reactor; J – duct for extraction of the gases out of the freeboard of the reactor; K – combustion air pre-heater; L – bag filters)

Due to the fact, that the torgas is directed to the gasifier, no auxiliary burner is needed to utilize it. Therefore it was possible to omit the use of fuel oil for the mass and energy balance of this installation.

The use of the torrefaction as a unit operation in such an installation might seem to be an unnecessary complication. However, it should not be overlooked that in this specific design (Fig.2) plasma gasification is used. Therefore, the use of torrefaction allows utilizing waste heat to remove a significant part of volatiles from the feedstock. If dried sewage sludge was to be fed directly to the plasma gasifier, part of the physical enthalpy of plasma would be consumed by pyrolysis. This, in consequence, would mean relatively higher consumption of electricity for plasma torches of the gasifier.

Performed mass and energy balance calculations (Fig.2) show, that the installation can indeed generate enough electricity to cover its own demand for plasma torches. A surplus of 53.0 kW\text{el} can be used to cover the demand for electricity, necessary for all of the auxiliary devices, such as fans, augers and PLC drivers, controlling the whole process. The use of plasma gasification system might seem a waste of valuable electricity. However, the ability to turn the inorganic part of the sewage sludge into a molten slag, which can be sold as a construction material, after initial pre-crushing, is valuable and eliminates the problem of landfilling of the solid residues from the typical thermal utilization systems.
for sewage sludge. Energy balance calculations for the plasma torches were based on own experience of the group and literature results for different types of waste [57, 64–67].

In terms of the heat loss in the vitrified slag, ash yield ($Y_a$) was used, to calculate the ash content of the torrefied material, as suggested by Wnukowski et al. [68] and Mościcki et al. [69]:

$$Y_a = Y_m \cdot \frac{A_{\text{product}}}{A_{\text{feedstock}}}$$

Specific heat of sewage sludge was adapted from Wang et al. [41]. Heat loss on the gas purification stage was calculated based on the assumed gas composition (based on own experience), temperature, and specific heat of main compounds [70].

The proposed system can be implemented in the water treatment plants, in towns with the total amount of inhabitants ranging from a couple of thousand up to 40 thousand (a typical small town in Poland). System does not require anaerobic digestion of the sewage sludge. Nonetheless, the use of anaerobic digestion brings some advantages as the producer gas from the gasification installation can be mixed with biogas, which, according to literature sources, leads to improved performance of a spark-ignition engine, using producer gas from gasification of sewage sludge [53].

4. Conclusions

This paper shows complete mass and energy balance of a novel installation for thermal utilization of the sewage sludge. Calculations were performed for the typical output of a wastewater processing plant in a middle size Polish town. Overall, the proposed configuration seems to be advantageous, due to the following reasons:

- Installation is fully sustainable and does not need external energy sources, due to maximized heat recovery from many different sources.
- The use of heat is optimized, by tapping to all the available heat sources, including low-quality heat, such as the latent heat of water vapors, present in wet air after drying.
- The use of torrefaction helps to lower the consumption of the electricity for subsequent plasma gasification.
- Plasma gasification is advantageous as it can potentially turn inorganic part of the sewage sludge into a marketable product.

The proposed system can be implemented in the water treatment plants, in typical small towns in Poland. The system does not require anaerobic digestion of the sewage sludge. Nonetheless, the use of anaerobic digestion brings some advantages as the producer gas from the gasification installation can be mixed with biogas.

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