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Sewage sludge gasification process for clean and sustainable environment

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Abstract. This work presents a multicriterial investigation of the sewage sludge gasification in the fixed bed gasifier. The operating parameters of gasification were varied over a wide range. Parameters such as air ratio $\lambda = 0.12$–0.27, gasification agent preheating $t = 50$–$250\,°C$ and gasification agent composition ($z_{O_2} = 0.21$ and $z_{O_2} > 0.21$) were found to influence syngas lower heating value and syngas composition.

1 Introduction

The quantity of sludge production in Europe [1–4] varies widely over different countries (16–94 g/(person day)). Moreover, the final of sewage sludge disposal depends on the sludge treatment methods used on the wastewater treatment plant.

Sewage sludge is a solid, semisolid, or liquid residue that results after the treatment process of waste water. Sewage sludge is an example of the biomass feedstock [5]. The composition of the organic fraction in biomass doesn't vary much. However, the variation of the moisture and ash content is large [6–8]. The most popular way of final sewage sludge management is storage. In countries that are technologically less developed, direct agricultural application or storage is typical pathways to safely dispose of stabilized sludge from wastewater treatment plants. In countries where policy makers practically forbade such solutions (e.g., the European Union), only thermal disposal methods are available [9–12]. The thermo-chemical conversion of sewage sludge consists of four main processes: combustion, co-combustion, pyrolysis and gasification. One of the promising thermo-chemical conversion technologies that can be used to convert sewage sludge to useful energy forms is gasification. This process has several advantages over a traditional combustion process [13]. First of all, as a consequence of the reducing atmosphere in the gasifier, gasification prevents emissions of sulphur and nitrogen oxides, heavy metals and the potential production of chlorinated dibenzodioxins and dibenzofurans. Due to it most of sulphur, nitrogen, chloride and fluoride in sewage sludge may be released as H_2S, NH_3, HCl and HF. Secondly, a less volume of gas is produced compared to the volume of flue gas from combustion [14–20].

This article reports on experimental investigations of fixed-bed gasification of sewage sludge. The operating parameters of gasification were varied over a wide range. Parameters such as air ratio $\lambda = 0.12$–0.27, gasification agent preheating $t = 50$–$250\,°C$ and gasification agent composition ($z_{O_2} = 0.21$ and $z_{O_2} > 0.21$) were found to influence syngas lower heating value (LHV) and syngas composition.

2 Experimental

2.1 Apparatus

The current study was conducted using a fixed bed gasification which was described earlier [21]. A scheme of the facility is shown in Figure 1.

The granulated sewage sludge was fed into the reactor. After approximately 120 min, the reactor was heated. The gasification cold air and preheated air flow rate/enriched air flow rate to the reactor was adjusted to ensure a specified air ratio. Once producer gas production began, the measurements of key parameters were started. As the sewage sludge was gasified, the ash produced was gradually discharged from the bed. The bed was maintained at a constant height by the addition of fuel at regular time intervals. A fraction of the gases produced during gasification was first passed through a condensing system which condensed out the condensables, followed by a set of filters for particulate removal to allow clean gas to enter the gas analyzer. Representative gas samples were also collected in Tedlar© gas bags for off-line measurements. The gases were subsequently analyzed using a chromatograph. The same procedure was repeated at different air ratios. Uncertainty in the measurements might have arisen from errors in the mass balances and volumetric apparatuses.

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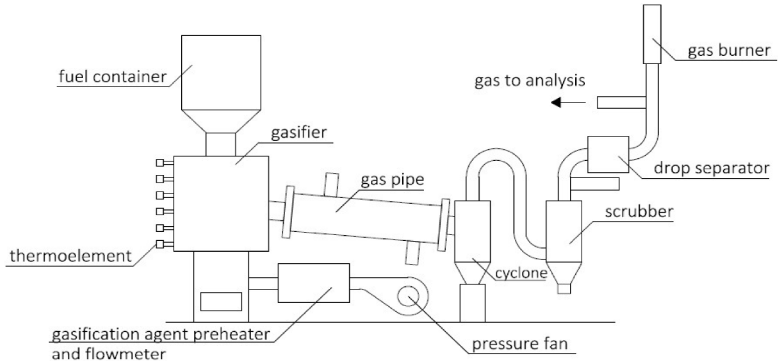


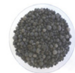
Fig. 1. Scheme of the experimental system.

2.2 Fuel properties

Two types of sewage sludge feedstock were analyzed.

Sewage sludge No. 1 (SS1) was taken from wastewater treatment plant operating in the mechanical–biological system and sewage sludge No. 2 (SS2) was taken from mechanical–biological–chemical wastewater treatment plant with phosphorus precipitation. In both analyzed cases, biological part of the wastewater treatment plant has worked with low load activated sludge. Thanks to it, effective removal of nutrients (phosphorus and nitrogen) from wastewaters is allowed. Additionally, in both analyses cases, sewage sludge is stabilized by anaerobic digestion and dehydration. After it, sewage sludge is dried. In the case 1 (SS1) sewage sludge was dried in cylindrical dryer with heated shelf. The temperature of hot air was equal to 260 °C (high temperature). In the case 2 (SS2) air belt dryer was used. The temperature of hot air in this case was equal to 150 °C (low temperature). As a consequence, in the case 1 form of the dried sludge is similar to granulate and in the case 2 to "noodles". Table 1 reports the properties of the analyzed sewage sludge.

Table 1. Properties of the fuel tested.

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 basis)		
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, kJ/kg dry basis	10,747	12,962
The sum of the PAHs, μg/kg dry basis	2433.40	621.33
The sum of the pesticides, μg/kg dry basis	18.85	1.28
The sum of the PCBs, μg/kg dry basis	66.86	12.47
Heavy metals, mg/kg dry basis		
Zn	920.90	991.20
Cu	495.30	183.16
Pb	119.30	59.97
Ni	103.67	18.90
Cr	180.53	584.53
Cd	6.47	3.24
As	4.19	3.94
Hg	0.99	0.96
Se	9.84	1.70
Sum	1841.19	1847.60

3 Result and discussion

3.1 Influence of the air ratio on the composition of syngas

Figure 2 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. Air ratio is a parameter that quantifies the amount of air/oxygen per unit mass of fuel, as compared to the theoretical amount of air/oxygen needed for complete combustion. Hence, the optimum air ratio that favors gasification resulting in combustible gases like CO, rather than the case of complete combustion with an air supply that mainly produces CO_2 need to be determined. In this study, a number of gasification experiments were done by varying the air ratio from 0.12 to 0.27. Analyzing Figure 2, 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 composition was found to be low and it starts to rise until the optimum air ratio of 0.18 and later drops for higher equivalence ratio. The maximum CO average composition values of 31.3% for SS1 (and 26.9% for SS2) were obtained for gasification at $\lambda = 0.18$. CO_2 shows an inverse relation

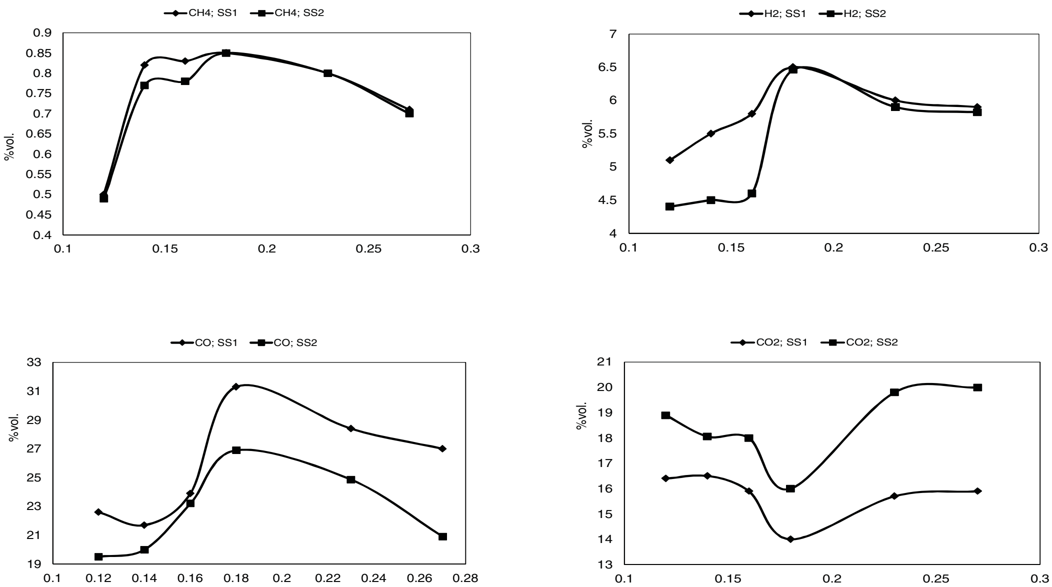


Fig. 2. Evolution of the main components in sewage sludge gasification gas as a function of the air ratio.

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 and 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 Figure 3, the dependence of LHV of obtaining gas versus an air ratio is presented.

The LHV in MJ/m^3n of the syngas was estimated using the formula given below [22]:

$$LHV = 0.126 \cdot CO0.108 \cdot H_20.358 \cdot CH_4. \quad (1)$$

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.

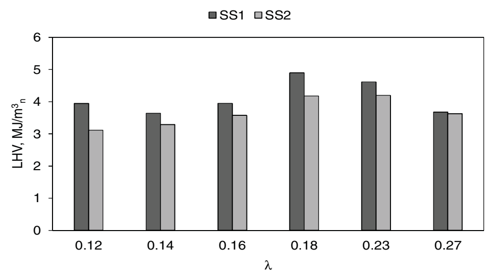


Fig. 3. LHV of the gasification gas versus air ratio.

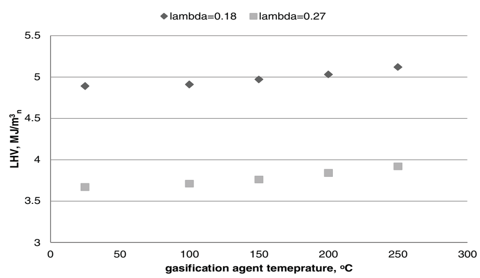


Fig. 4. Influence of the gasification agent temperature on the LHV of the syngas.

3.2 Influence of the temperature of gasification agent on syngas composition

Figure 4 demonstrates that the use of hot air for sewage sludge gasification was able to produce gasification gas with a superior heating value compared to low temperature gasifiers, which produce producer gas with LHVs ranging up 5.12 MJ/m^3n.

It is caused by the increment of the yield of the main producer gas components, CO, H_2 and CH_4, which were enhanced by increasing the gasification agent

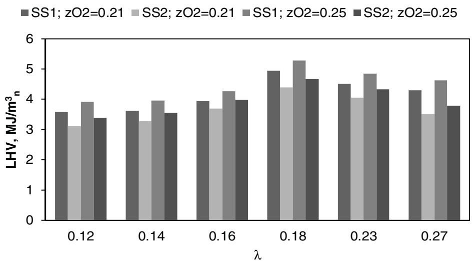


Fig. 5. Influence of the gasification composition on the syngas LHV.

temperature. This is mainly due to the involved endothermic reactions in the gasification process which become more dominant at higher temperatures. Similar behavior is also found during catalytic gasification. The high temperature of gasification agent was sufficient to allow for secondary thermocracking reactions that increased the producer gas yield.

3.3 Influence of the gasification agent composition on syngas composition

Figure 5 shows the influence of the gasification agent composition on the LHV of producing gas. The gasification agent studied is composed of nitrogen and oxygen mixtures. The oxygen molar concentration studied were equal to: 21% and 25%. Analyzing Figure 5, it concludes that LHV of the producer gas slightly increases with the increment of the oxygen concentration in gasification agent. This is mainly caused by the lower dilution by the nitrogen.

4 Conclusions

The main conclusions from the study are as follows:

– The operating conditions (amount of the gasification agent) of the sewage sludge gasification process greatly influence the syngas composition distribution.
– Higher values of the main components (especially C and H) in the sewage sludge plant affect on the increase of the LHV of gasification gas.
– Throughout the range of analyzed air ratio ($\lambda = 0.12$–0.27) 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.
– 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.
– The yield of the main producer 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.

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