CHEMICAL ENGINEERING TRANSACTIONS

VOL. 80, 2020

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Eliseo Maria Ranzi, Rubens Maciel Filho
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ISBN 978-88-95608-78-5; **ISSN** 2283-9216

DOI: 10.3303/CET2080030

Gasification of Sewage Sludge in a Bench-Scale Reactor

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The handling of sewage sludge is one of the most significant issues of wastewater treatment plant due to its potential harmful environmental impact and remarkable disposal costs. As a consequence, a proper handling of this biowaste is needed.

In the present study, a bench-scale fixed bed gasifier was operated with a sewage sludge coming from a drying facility. The experimental runs have been carried out using for each test 30 g of dried sewage sludge, steam as gasifying agent and by varying the reactor temperature in the range of 700 – 850 °C.

The results indicated that the gasification test conducted at a temperature of 700 °C produced the highest concentration of hydrogen, 58.2%. In addition, the increase of reaction temperature determined a reduction of char and tar from 11.4 to 9.7 g and from 9.1 to 0.7 g, respectively. On the other hand, the cold gas efficiency increased from 11 to 50%.

1. Introduction

Population growth and more severe waste management regulations determined an increasing amount of wastewater to be treated. During wastewater treatment process sewage sludge (SS) is by far the largest by-product generated, therefore its handling is one of the most significant issues of wastewater treatment plant.

In the EU, the production of SS is estimated at about 10 million tons per year (on dry basis). Currently, the traditional options in SS management are the use as agriculture fertilizer, landfilling and incineration (Fytili and Zabaniotou, 2008). Land application of SS can improve soil properties (nutrient content, porosity, water retention, etc.). On the other hand, they also contain heavy metals and pathogens that can cause crop, soil and groundwater contamination, thus representing a risk to human health.

In addition, EU legislation limited the organic fraction in landfilling (Council directive 99/31/CE), and there are still concerns by local communities about the environmental effect of incinerators. As a consequence, conventional disposal methods for SS are becoming less feasible (Chen et al., 2017).

Emerging trends in this field (i.e. hydrothermal treatment, pyrolysis and gasification) are gaining increasing researchers’ attention. In particular, SS gasification offers several advantages, such as: reduction of the solid residues that must be disposed, destruction of toxic organic compounds, minimization of nasty odour dispersion, production of a gas that can be used to produce electrical and thermal energy.

Gasification is a thermo-chemical process that converts carbonaceous materials into useful gaseous fuels or chemical feedstocks (Basu, 2013). Gasification is widely accepted due to its greater environmental sustainability (Zaccariello and Mastellone, 2015) and for its considerable operating flexibility. In particular, gasification process allows the simultaneously feeding of different kind of fuels (Mastellone et al. 2012); the utilization of various gasifying agents (Arena et al. 2010); the use of a specific catalyst (Mastellone and Zaccariello, 2013a); the addition of reactants into the reactor (Mastellone and Zaccariello, 2013b). On the other hand, during the gasification process, the formation of contaminants such as tar, carbonaceous particles, and inorganics leads to an increase in operating costs and efficiency loss. As a consequence, further researchers’ efforts are needed to eliminate or strongly reduce the formation of these by-products.

Steam gasification may allow to obtain a high syngas quality from alternative carbonaceous feedstock. Rapagnà and Spinelli (2015) performed steam and air-steam biomass gasification tests in absence and in

Paper Received: 16 November 2019; Revised: 25 February 2020; Accepted: 15 April 2020
Please cite this article as: Zaccariello L., Mastellone M.L., 2020, Gasification of Sewage Sludge in a Bench-scale Reactor, Chemical Engineering Transactions, 80, 175-180 DOI:10.3303/CET2080030

presence of catalytic and non-catalytic ceramic filters. The results showed that during the test with only steam the catalytic filter increased its effectiveness to reduce tar, CH_4 and NH_3 in the syngas. The same Authors (Rapagnà, Spinelli, 2016) studied the effect of olivine and dolomite as in-situ catalytic bed material on the syngas composition obtained during air-steam biomass gasification tests. It was observed a drastic reduction of tar (57 mg/Nm^3) during the test with steam as gasifying agent and a fluidized bed composed of 80% of olivine and 20% of dolomite. In addition, due to the utilization of ceramic filters in the freeboard, the hot gas that leaves the reactor is free of solid particles.

Herman et al. (2016) utilized coal bottom ash as catalyst for steam gasification of palm kernel shell in a thermogravimetric analyser coupled with mass spectrometer varying the temperature from 650 to 750 °C. The results indicated that the highest hydrogen content was obtained at a temperature of 700 °C, while the concentrations of carbon monoxide, carbon dioxide and methane were 24.7, 1.4, and 37.3% respectively. In addition, the Authors attributed the low amount of carbon dioxide and the very high concentration of methane to the presence of CaO in the coal ash.

Iven if in the scientific literature several interesting research studies can be found, the know-how of SS steam gasification is far from exhaustive. Further research efforts are needed to optimize process parameters and explore new reactor design solutions. This experimental work aims to investigate the effect of reaction temperature, a crucial operating parameter, on the performance of the steam gasification of SS, which is expected to produce a syngas with high percentage of hydrogen and a reduced amount of tar.

2. Experimental Section

2.1 Experimental apparatus

The experimental work was carried out utilizing a bench-scale fixed bed gasifier (FBG) with a maximum feedstock capacity of 100 g, depending on the type of fuel (Figure 1).

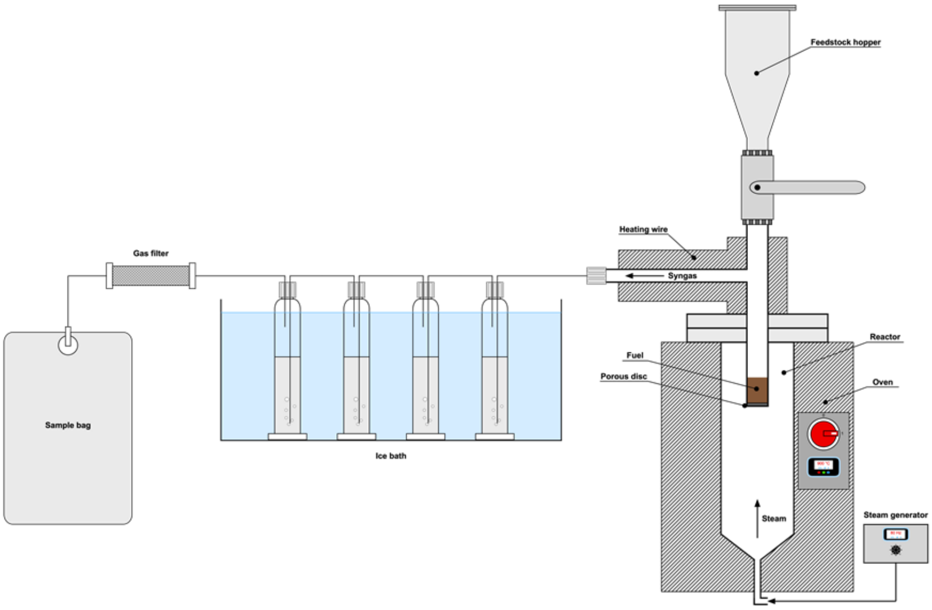

Figure 1: Schematic illustration of the bench-scale fixed bed gasifier

The experimental apparatus is composed of an oven, a steam generator, a fixed-bed reactor and a gas condensation/cleaning line. The oven allows to increase the reactor temperature from room temperature to reaction temperature (up to 1000 °C). It is controlled by a thermoregulator connected to a thermocouple located in the pre-heater. The steam, coming from the steam generator, enters the pre-heater – a cylindrical column with an internal diameter of 10 cm – from the bottom and is heated up from 200 °C up to the selected reaction temperature. Then, the superheated steam, through a porous disk reaches a coaxial cylinder where, once the reaction temperature is reached, the SS is discharged from the hopper. In this region the gasification reactions take place. At the reactor exit a gas conditioning line, composed by four bubblers filled with dichloromethane and by a cotton filter, provides for tar and particulate removal/collection. Then, the syngas coming from the gas treatment section is collected in multi-foil gas sampling bags and immediately analyzed in an Agilent 490 micro gas chromatograph. The micro-GC measurements provide the main syngas compounds (CO_2, CO, H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8, and N_2).

Elutriated fines, collected by the bubblers and cotton filter, were analyzed in a LECO CHN/S 628 in order to evaluate the content of carbon, hydrogen, nitrogen, and sulfur.

After water separation, the tar dissolved in dichloromethane where quantified removing the solvent in a rotavapor. Then, the tar is diluted in a specific ratio in dichloromethane and analyzed off-line in a Thermo Fisher Scientific ISQ 7000 gas chromatograph coupled with a mass spectrometer (GC-MS).

With the purpose of obtain reliable data, the sampling procedures of syngas, particulate, and tar where activated for the entire duration of the tests.

2.2 Operating conditions

The experimental runs have been carried out by keeping fixed the feedstock amount (30 g), the reaction time (30 min) and the gasifying agent (2 g/min of superheated steam) and by varying the reactor temperature between 700 and 850 °C.

2.3 Feedstock

The bench-scale FBG was operated with SS supplied by an Italian sewage sludge drying facility located in the Lazio Region. Design and operation of gasification process need fuel composition as well as its chemical energy content. In the present study two types of analyses are performed: proximate and ultimate analyses. The proximate analysis provides moisture, volatile matter, fixed carbon, and ash content, while the ultimate analysis gives the fuel composition in terms of its basic elements such as carbon, hydrogen, nitrogen, sulfur, and oxygen. In this work the proximate analysis was performed as follows: the gross fuel sample was heated in air to 105 °C for 12 h to obtain moisture content, to 950 °C in inert ambient (nitrogen) for 7 minutes to obtain volatile matter (VM), and to 600 °C in air for 4 h to obtain ash amount. Finally, the fixed carbon (FC) that remains after drying and devolatilization was calculated by subtracting the percentage of moisture, volatile matter, and ash from 100%. The ultimate analysis was carried out processing the fuel sample in the LECO CHN/S 628 Analyzer.

The higher heating value (HHV) was evaluated by means of the Equation 1 (Channiwala and Parikh, 2002) while the lower heating value (LHV) was evaluated by the Equation 2.

$$HHV = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1Ash \qquad \text{Eq(1)}$$

$$LHV = HHV - 2581 \times (Moisture + 8.76H) \qquad \text{Eq(2)}$$

Results of proximate and ultimate analyses and energy content of the tested fuel are listed in Table 1.

Table 1: Main properties of the dried sewage sludge

Ultimate analysis (wt.%)					Proximate analysis (wt.%)				Energy content (MJ/kg)	
C	H	O	N	S	Moisture	VM	FC	Ash	HHV	LHV
21.1	3.0	10.1	2.4	0.6	25.3	35.4	1.8	37.5	12.2	10.6

3. Results and Discussion

The high flexibility of the gasification process is also related to the possibility of utilising different gasifying agents. The gasifying medium affects the selectivity of the reactions occurring during the process and, as a consequence, the syngas composition. Steam gasification is an attractive alternative process which could allow to obtain a syngas with high percentage of hydrogen from low-grade fuels (Nipattummakul et al., 2010).

Table 2: Main results of experimental runs

Test -	T °C	H_2 %	CH_4 %	C_4H_m %	CO %	CO_2 %	Gas Yield dm^3/kg$_{SS}$	LHV MJ/ kg$_{SS}$	W_{Char} g	W_{Tar} g	CGE %
1	700	58.2	11.5	1.1	13.7	15.5	126.2	12.8	11.4	9.1	11.0
2	750	53.0	8.9	1.8	11.8	24.6	172.8	11.5	11.0	8.0	13.5
3	800	51.4	7.0	2.8	10.6	28.1	605.3	11.2	10.2	0.9	46.3
4	850	51.2	7.2	3.0	10.9	27.8	644.8	11.4	9.7	0.7	50.3

The bench-scale FBG was feed with SS under various experimental conditions in order to obtain information about the role of the reactor temperature on the performance of the steam gasification process. The main experimental results are reported in Table 2.

The results indicated that the steam gasification of SS produces a syngas very reach in H_2: all the tests generate a syngas with a concentration of H_2 larger than 50%. In particular, Figure 2 shows that the H_2 concentration decreases from 58.2 to 51.2% as the reaction temperature was increased from 700 to 850 °C. Similar trends are observed for CH_4 and CO, where their concentrations decrease from 11.5 to 7.2 and from 13.7 to 10.9, respectively. On the other hand, the amount of C_4H_m (i.e. light hydrocarbons with $C \leq 4$) and CO_2 increases from 1.1 to 3.0% and from 15.5 to 27.8%, respectively.

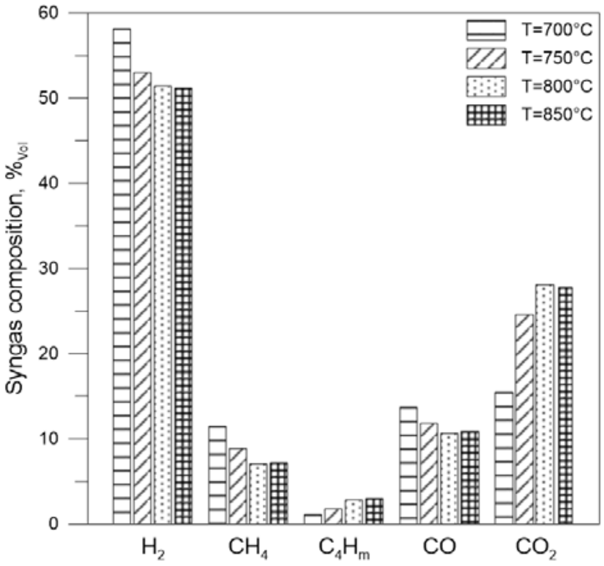

Figure 2: Concentration of the main components of the dry syngas.

These results can be explained considering the reactions R1–2.

$$C + H_2O \leftrightarrow CO + H_2 \quad \text{R1}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad \text{R2}$$

Higher temperature should thermodynamically favour the water-gas reaction (R1) and moderates the water-gas shift reaction (R2). Therefore, an increasing concentration of H_2 and CO was expected. Otherwise, the results indicate, in these specific experimental conditions, an opposite trend (i.e. a decreasing of H_2 and CO).

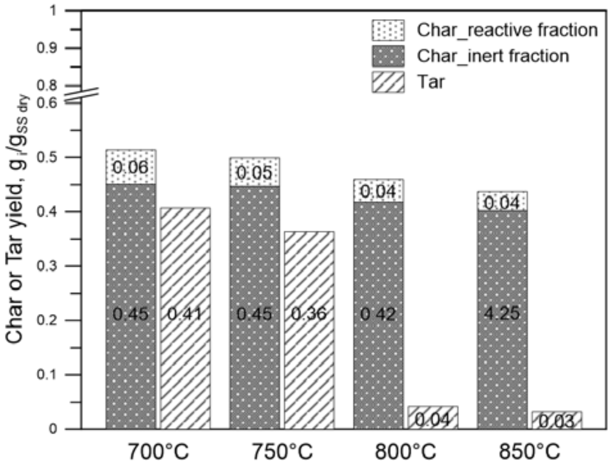

Figure 3: Char and tar produced during the gasification tests

A possible explanation could be due to the higher extension of gasification reactions at elevated temperatures, which increase the conversion of char and tar to permanent gas. This hypothesis is supported by the increase in the yield of H_2 (from 6.6 to 29.7 g/kg$_{ss\ dry}$), CH_4 (from 10.3 to 33.1 g/kg$_{ss\ dry}$), CO (from 21.6 to 87.6 g/kg$_{ss\ dry}$) and CO_2 (from 38.4 to 351.6 g/kg$_{ss\ dry}$), by the considerable reduction of char and tar (Figure 3) and by the higher production of syngas (Figure 4A), as the temperature increased from 700 to 850 °C.

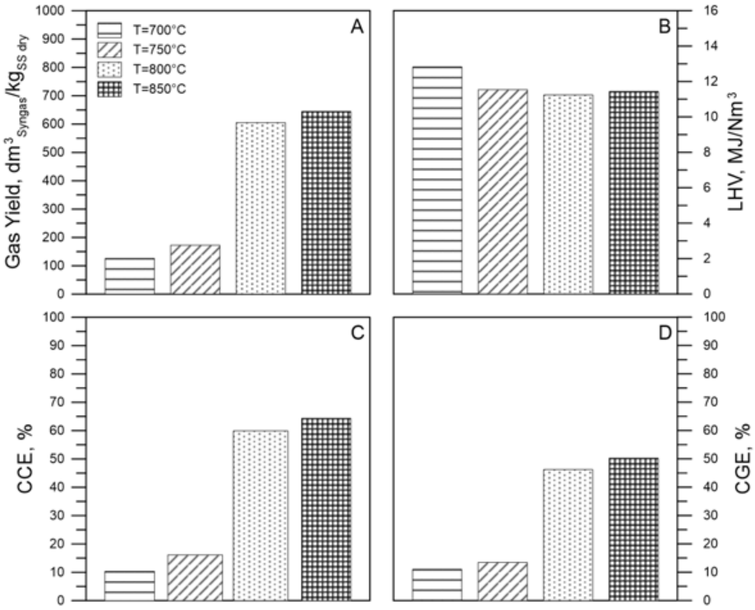

Figure 4: Parameters of process performance as obtained during the gasification tests

Similar results were obtained by Chen et al. (2017) during the steam gasification of dried SS using CaO as CO_2 sorbent in a laboratory scale fixed bed reactor. The Authors attributed the increase in both syngas and H_2 yields to the decomposition of tar and conversion of char, which intensified at higher temperature. In this case, H_2 fraction reduced while CO_2 fraction and H_2 yield increased. Lee et al. (2018) conducted SS gasification tests using steam as gasifying agent in a lab-scale system. The experimental runs were performed at 1000 °C and varying the steam flow rate from 2.5 to 20 g/min. In the runs with a similar flow rate of steam (2.5 versus 2 g/min), comparable concentrations of H_2 (about 47 versus 51%) and CH_4 (about 8 versus 7%) can be observed. On the other hand, higher concentration of CO (about 34 versus 11%) and a lower concentration of CO_2 (about 13 versus 28%) were found. In addition, the Authors reported a syngas yield significantly higher than that obtained in this work (920 versus 645 Ndm^3/kg$_{SS}$ dry). These differences could be attributed to the higher reaction temperature (1000 versus 850 °C) which promotes the gasification reactions and, as a consequence, a higher amount of valuable syngas.

Table 3: Elemental composition and ash content of the char

Test	C	H	O	N	S	Ash
-			wt.%			
1	10.56	0.89	0.03	0.69	0.07	87.76
2	9.17	0.73	0.02	0.52	0.06	89.50
3	8.19	0.37	0.01	0.41	0.22	90.80
4	7.37	0.23	0.02	0.29	0.19	91.90

One of the most significant effects of steam utilization as gasifying agent is the considerable conversion of tar and carbonaceous solid particles to syngas. Figure 3 shows that the use of steam produces an impressive reduction of tar which decreases of about 92%, as the temperature increases from 700 to 850 °C. The conversion of char is less marked due to its reduced reactivity and to the considerable amount of inorganic fraction (Table 3). It is observed an overall char reduction of about 15%, while the conversion of the reactive fraction (sum of carbon, hydrogen, oxygen, nitrogen and sulphur amounts) is about 44%.

The conversion of char and tar into permanent gas determined an increase of gas yield from 126.2 to 644.8 Ndm^3/kg$_{SS\ dry}$ (Figure 4A), an increase of carbon conversion efficiency (CCE) from 10.3 to 64.4% (Figure 4C) and an increase of cold gas efficiency (CGE) from 11.0 to 50.3% (Figure 4D). On the other hand, LHV decreases from 12.8 to 11.4 MJ/Nm$^3_{Syngas}$ substantially due to the considerable increase of CO_2 at higher temperatures (Figure 4B).

4. Conclusions

The results indicate that the steam gasification reactions of SS significantly enhanced above 750 °C. Higher temperatures determined a considerable conversion of tar and char to syngas. It was observed a tar reduction of about 92%, while the conversion of char was less marked due to its considerable inorganic fraction content. The larger extension of gasification reaction at higher temperatures determined an increase of gas yield, CCE and CGE. On the other hand, LHV decreased due to the considerable increase of CO_2 in the syngas.

The process produced a valuable syngas with a hydrogen concentration larger then 50%. The impressive concentration of hydrogen in the syngas make the process interesting in a view of clean fuel production. However, further efforts are required to reduce the concentration of tar which could prevent the use of the syngas in the end-user devices.

Acknowledgments

The authors are indebted to Sara Salomone who contributed to perform the experimental runs and the offline analysis.

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