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Air-steam gasification of char derived from sewage sludge pyrolysis. Comparison with the gasification of sewage sludge

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HIGHLIGHTS

- Increased content of fixed carbon in the solid after sewage sludge pyrolysis.
- Higher gas yield from dried and ash-free (*daf*) char than from sewage sludge (*daf*).
- Average tar yield decreased by 45% when gasifying char instead of sewage sludge.
- Average CO yield was 70% higher when gasifying char (*daf* basis for solids).
- Temperature was the most influential factor for most of the studied variables.

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ABSTRACT

Air-steam gasification of char derived from fast pyrolysis of sewage sludge has been experimentally evaluated in a fluidized bed as a route towards a full recovery of energy from sewage sludge. The results have been compared with those obtained from the direct gasification of sewage sludge in order to evaluate how the previous pyrolysis stage affects the subsequent gasification process. The fixed carbon content in the solid increased after the pyrolysis stage so that heterogeneous reactions of carbon with steam or CO_2 assumed greater importance during char gasification than during sewage sludge gasification. Furthermore, char gasification led to an improvement in the gas yield -calculated on a dry and ash-free basis (*daf*)- due to the increased concentration of carbon in the organic fraction of the solid after the pyrolysis step, with an increase in the average CO yield of about 70% -in terms of g/kg solid *daf*-. The reduction in the fraction of carbon which forms tar is another advantage of char gasification over the direct gasification of sewage sludge, with an average decrease of about 45%. Regarding the influence of the operating conditions, the response variables were mainly controlled by the same factors in both processes.

1. Introduction

Sewage sludge is the waste generated during successive treatment stages of urban wastewaters. In recent years the production of sewage sludge in the EU has considerably increased due to the expansion in the amount and capacity of wastewater treatment plants [1,2]. For instance, the production of sewage sludge in Spain increased by 41% in the period 2000–2009 [3]. For this reason, the economical and environmentally-friendly treatment of sewage sludge has become an important issue. The traditional methods of treatment or disposal of sewage sludge include its use as fertilizer on croplands, incineration and landfilling [1,2,4]. However, as a result of the environmental and health problems caused by the application of these techniques, energy recovery from sewage sludge by thermo-chemical treatments such as pyrolysis or gasification technologies could be an interesting alternative [2].

A large number of lab-scale studies on sewage sludge pyrolysis for liquid production (fast pyrolysis) can be found in the literature [5–11]. The liquid yield and its physicochemical properties depend on the operational conditions (mainly on the temperature) and on the composition of the sewage sludge [6]. Char is the main by-product of sewage sludge fast pyrolysis. Common solid yields of around 35–55 wt.% are found in the literature [8–11], but it should be noted that the ash content in these solids is much higher than those of lignocellulosic origin. The use of this solid by-product as adsorbent material has been investigated by some authors. The results show that char obtained from sewage sludge pyrolysis is not a very porous material (its surface area ranges 50–150 m^2/g) because of its high inorganic content [12]. Despite this, some

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authors have reported a certain capacity of this kind of material to remove contaminants such as H_2S, NO_x, metals, dyes and phenols [12–16]. Physical activation of this kind of char was proposed as part of a three-stage thermo-chemical treatment of sewage sludge in a previous work in our group [17].

On the other hand, the remaining organic fraction in char gives it a moderate calorific value which could be further exploited through thermo-chemical processes. In fact, the gasification of char resulting from fast pyrolysis of different types of biomass is being investigated by some authors as a route towards an integral valorization of biomass [18–22]. Furthermore, as part of volatile matter is removed from biomass during pyrolysis, the gasification of char obtained from pyrolysis instead of the direct gasification of biomass should lead to a reduction in the formation of tar during the process, which is one of the main hurdles for the development of gasification technology.

The present work is focused on the gasification of char obtained from sewage sludge fast pyrolysis. An experimental study has been carried out in a lab-scale fluidized bed reactor in order to evaluate the feasibility of gasifying this kind of char. The influence of several operating conditions (temperature, composition of the gasification medium and gasifying agent to biomass ratio) on the gasification performance has been analyzed statistically in order to determine the relative influence of each factor. Moreover, results from char gasification have been compared with those obtained from the direct gasification of sewage sludge under the same operating conditions [23] in order to evaluate how the previous pyrolysis stage affects the subsequent gasification process.

2. Materials and methods

2.1. Char obtained from sewage sludge pyrolysis

Char obtained from the fast pyrolysis of anaerobically digested and thermally dried sewage sludge is the feedstock for the gasification experiments performed in this work. Table 1 presents the results of the proximate and ultimate analyses and heating value of the char, as well as the results obtained for the original sewage sludge. The fixed carbon content in this kind of char is considerably lower than in other types of biomass chars [18–22] as the composition of sewage sludge and lignocellulosic materials are quite different.

2.2. Experimental setup

Char was produced during sewage sludge fast pyrolysis in a lab-scale fluidized bed reactor operating at a temperature of 530 °C. The pyrolysis plant and the operating conditions are described in detail elsewhere [24].

Table 1
Proximate and ultimate analyses and lower heating value of both the char derived from sewage sludge pyrolysis and the sewage sludge itself (SS).

		Char	SS
Proximate analysis (wt.%, wet basis)			
Moisture	ISO-589-1981	1.70	6.48
Ash	ISO-1171-1976	74.20	39.04
Volatiles	ISO-5623-1974	15.02	50.09
Fixed carbon	By difference	9.08	4.39
Ultimate analysis (wt.%, wet basis. Carlo Erba 1108 elemental analyzer)			
C		15.49	29.50
H		0.97	4.67
N		1.85	5.27
S		0.35	1.31
LHV (MJ/kg)	IKA C-2000 calorimeter	5.0	11.8

Char gasification experiments have also been carried out in a lab-scale fluidized bed reactor operating at atmospheric pressure, with continuous feed of solid (around 2.1 g/min of char) and continuous removal of ash. Ash from previous gasification tests constituted the solid bed by itself from the beginning of the runs. The gasifying/fluidizing agent used in the process consisted of different mixtures of steam and enriched air (air + oxygen). Air flow was kept constant in all the experiments and different flows of pure oxygen were fed together with the air, thus enriching the air at different percentages.

The vapors and gases produced during the gasification process remained inside the reactor around 17–18 s and then passed through a cyclone and a hot filter (both at 450 °C) in which the solid particles swept by the gas were collected. Water and condensable organic compounds (tar) were collected in two ice-cooled condensers. The volume of particle- and tar-free gas was measured by a volumetric meter and its composition was analyzed on-line using a micro gas chromatograph (Agilent 3000-A). The experiments were carried out during 60 min. Fig. 1 shows a diagram of the laboratory installation. A more detailed description of the plant can be found elsewhere [23].

Ash content in the solid by-product was determined according to ISO-1171-1976 and its carbon content was analyzed using a Leco TruSpec Micro Elemental Analyzer. Water content in the condensed fraction was analyzed off-line by Karl Fischer titration in order to determine the amount of tar by difference. However, tar production was almost negligible and all the results from the Karl Fischer titration were about 100 wt.% of water, so non-significant differences in tar production were found by this way. Therefore, in order to evaluate the effect of the factors, tar production from char gasification was approximated to the amount of organic carbon present in the condensate (g $C_{condensate}$), measured by means of a total organic carbon analyzer (TOC-L CSH/CSN Shimadzu analyzer).

2.3. Experimental design and data analysis

A 2^k factorial experimental design was planned in order to determine the influence of some operating factors on the char gasification performance. This kind of experimental design allows the existence of interactions between the factors to be identified. In other words, it can be seen whether a factor influences a response variable in a different way depending on the value of another factor.

Three factors have been studied in this work: (i) gasification temperature, measured inside the bed (ranging between 770 and 850 °C); (ii) gasifying ratio (*GR*) between the mass flow of gasifying agent (oxygen plus steam) and the mass flow of dry and ash-free (*daf*) basis char (ranging between 0.8 and 1.1 g/g char *daf*) and (iii) composition of the gasification medium, represented by the H_2O/O_2 molar ratio (ranging between 1 and 3). The three studied factors, together with their respective ranges of study, were chosen based on our previous work on sewage sludge gasification [23] in order to compare the performance of both processes and evaluate how a previous pyrolysis stage affects the subsequent gasification process. The temperature and the ratio between the flow of oxygen or steam and the feed of biomass are among the most studied factors in the air-steam gasification of biomass [22,25].

As seen in Table 2, the experimental design consisted of 8 runs (2^k runs, where k is the number of factors, in this case 3). Furthermore, three replicates at the center point (CP) were added to the experimental design in order to evaluate the experimental variability as well as to determine if the response of each variable was linear or not within the studied range. Coded values of the factors were used to identify the term with the greatest influence on each response variable, that is, -1 for the lower limits ($T = 770$ °C, $GR = 0.8$