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Research article

Application of fast pyrolysis char in an electric arc furnace

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ABSTRACT

The feasibility of applying char obtained from wheat straw fast pyrolysis as charge carbon in an electric arc furnace (EAF) for the production of steel was investigated. Fast pyrolysis char represents a by-product which could be made available at reasonable cost. It is characterized by higher volatile content than slow pyrolysis char. Prior to application in the EAF, agglomerates with good strength characteristics were formed from the char by adding water and molasses as binder material. Minerals content, specifically potassium, was increased by this procedure which possibly limits the use in an EAF. The burn-off characteristics of these agglomerates in the EAF proved to be feasible. Further experiments in industrial scale can be recommended based on the results of this pilot study with special focus on balancing the minerals in the process.

1. Introduction

The transformation of biomass to valuable materials plays an important role for the establishment of a bioeconomy that will significantly contribute to the climate targets agreed upon between almost all countries in the world [1]. Biofuels are important products because carbon based fuels are likely to keep a significant share, also in future mobility scenarios. Similar to biofuels, material use of biobased products represents an efficient way of establishing a bioeconomy because they make use of biomass as a renewable carbon instead of biomass as a renewable energy source. From the viewpoint of reducing carbon emissions, the most efficient material applications are those that directly replace fossil coal, e.g. for the production of activated carbon [2] and as catalyst and catalyst support material [3]. Another important industrial use of fossil coal is in the different processes of steel making and the potential of replacing fossil resources with biobased materials has been reviewed recently [4]. It was shown that most of the scientific work dealing with this application was conducted for substituting fossil coal in blast furnaces. Less work was conducted to investigate the use of biomass/biomass derived materials in electric arc furnaces (EAF), which are widely used to produce steel from recycled steel scrap.

The CO_2 emission reduction potential in EAFs is highest when charge carbon and the slag foaming agent are being replaced [5]. The average amount of coal/coke used in the EAF is about 12 kg/t steel [6], which is equivalent to CO_2 emissions of about 43 kg CO_2/t steel (assuming high quality metallurgical coal/coke). Based on 12.6 million tons of steel produced in EAFs in Germany in 2016, these specific consumption and emission values equal to a consumption of about 150,000 t coal/coke and emissions of about 540,000 t CO_2. Preliminary thermal analyses of grape seed and pumpkin seed char showed a general suitability of these chars in an EAF for both applications, depending on the amount of volatiles in the char [7]. Specifically the sustained release of volatiles of biomass derived char was reported to lead to favorable slag foaming properties [8]. First application of biochar fines from gasification and pyrolysis in an EAF revealed that reactivity is crucial for a feasible application [9]. The high reactivity of small particles lead to unfavorable burn-off and it was shown that agglomerates produced from these fines behave similar to the reference coal material. As with many other applications, the cost of specifically producing char from biomass, even agricultural residues, is still the major obstacle for an industrial implementation.

This study investigates the use of char from fast pyrolysis for application in EAFs. Since fast pyrolysis aims at producing liquid products from biomass, char is often regarded an unwanted byproduct and consequently available at potentially lower cost than char produced by dedicated carbonization processes such as slow pyrolysis. Industrial applications of fast pyrolysis typically burn the produced char within the process to provide heat [10–12]. The material use in steel making processes such as in an EAF would represent a value added use and directly replaces fossil coal, increasing the CO_2 reduction potential

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significantly. It was shown that char produced from fast pyrolysis exhibits a lower degree of aromaticity than slow pyrolysis and gasifier char [13], giving rise to the need for investigating this particular material because it is consequently to be expected that the amount and nature of volatiles is different, too. One focus of this study is on the production of agglomerates with sufficient strength characteristics for the use in EAFs. A second focus is the ash content of the produced char, which is also very important for the application in EAFs [4]. Many agricultural residues, such as wheat straw, exhibit high ash content which further accumulates in the char during pyrolysis. Finally, burn-off characteristics in an EAF are determined as decisive criterion for the applicability of fast pyrolysis char based on previous experimental experience [8].

The char for this study was obtained from wheat straw fast pyrolysis (10 kg h^{-1} feed capacity), which is conducted as part of the bioliq® concept [14,15]. In this concept, char is not burned inside the fast pyrolysis process and thus is readily available to alternative, value added applications [16]. Since char needs to be separated from pyrolysis vapors prior to condensation, char could also be made available in other fast pyrolysis processes. Compression of this char is required to form agglomerates with a sufficient strength and reduced reactivity. Both water and molasses were added in the present study to form the agglomerates. Water is very effective for agglomeration of biomass and lignite because of the strong hydrogen bridges between water and functional groups of the material as well as Van der Waals forces (orientation, induction, dispersion forces) [17–19]. Hard coal and biomass char contain lower amounts of functional groups and their hydrogen bridges to water cannot achieve a sufficient strength of the agglomerate; consequently binders are needed [17]. The addition of binders like molasses or starch results in solid bridges between material particles and binder, improving stability and strength of the agglomerate [20]. The produced agglomerate was finally tested in an EAF (40 l capacity one batch) to validate feasible burn-off characteristics. Consequently, the whole study was conducted in pilot scale to produce representative results for a potential industrial application.

2. Material and methods

2.1. Materials

The feedstock used for the experiments was wheat straw (*Triticum aestivum L.*) from a harvest of spring wheat (Dörrmann in Kraichtal-Münzesheim, Germany). It was supplied in large bales (250–300 kg each) and cut to a particle size of < 5 mm in the pretreatment section of the bioliq® pilot plant. The pretreatment is comprised of a disintegrator (HZR 1300) followed by a cutting mill (LM 450/1000-S5-2), both supplied by Neue Herbold Maschinen- und Anlagenbau GmbH (Sinsheim/Reihen, Germany). The feedstock characteristics are summarized in Table 1. Due to its high ash content it is required to compare many characteristics on a dry, ash-free mass basis. A thermogravimetric analysis is illustrated in Fig. 1 which shows typical peaks for the major components cellulose (325 °C), lignin (broad peak up to roughly 600 °C), and hemicellulose (merged with cellulose peak, shoulder at lower temperature). The mass loss of volatiles up to 800 °C was measured to 76.1% on a dry, ash-free mass basis (excluding evaporation of water).

Commercially available molasses was used as binder material (Organic Blackstrap Molasses, Meridian Foods Limited). Analyses are included in Table 1. It is noted that due to foaming problems associated with the sample matrix, analysis of the water content shows higher standard deviation than typically observed for the applied method.

Table 1
Feedstock characteristics. All values represent mass fractions.

Parameter	Wheat straw	Molasses
Water content, as received (%)	8.9(± 0.7)	18(± 1)
Ash content, dry (%)	8(± 1.8)	n.d.
C, dry (%)	46.3(± 0.4)	41(± 0.5)
H, dry (%)	5.7(± 0.1)	6.2(± 0.1)
N, dry (%)	< 2.4	< 0.4
Other elements > 1 g kg^{-1}, dry (g kg^{-1}):		
Si	18(± 4.7)	2[b]
K	14(± 2.3)	16[b]
Cl	2.4(± 0.9)	2[b]
Ca	3.6(± 0.8)	7[b]
P	0.8(± 0.3)[a]	< 1[b]
Mg	0.9(± 0.3)[a]	2[b]

n.d.: not determined.

[a] Included because concentration > 1 g kg^{-1} in the produced char.

[b] Single measurements.

2.2. Pyrolysis pilot trials

Pyrolysis experiments to produce the required batches of char were conducted in a fast pyrolysis process development unit with a feedstock capacity of 10 kg h^{-1} operated at KIT and described in detail elsewhere [21]. The biomass feedstock is converted at 500 °C in an airtight twin-screw mixing reactor that realizes the required high heat transfer by mechanical agitation of the biomass with preheated steel balls as heat carrier material. The product recovery consists of solid separation by a cyclone at reactor temperature followed by a two staged condensation. The process was designed for conversion of wheat straw with high ash content which demands a two staged condensation in order to avoid a two-phase bio-oil [22,23]. The quench to condense the first condensate fraction at around 90 °C, the organic-rich condensate, is operated with the produced condensate after recirculation and cooling. The same product recovery is operated in pilot scale (500 kg h^{-1} feedstock capacity) and has been proven to be suitable for conversion of this ash-rich biomass residue [14]. Aerosoles are removed in an electrostatic precipitator and collected together with the organic-rich condensate. The second condensation stage is operated between 15 and 20 °C and non-condensables vented after analyses. The separated char was cooled down in inert atmosphere (nitrogen) for at least 24 h before being transferred to the storage container.

Char was collected from a total of nine experimental runs due to the high amount of material needed for the planned experiments in the EAF. The experimental conditions were controlled as close as possible; however, there were some major deviations between experimental runs due to the heterogeneity of the feedstock in ash content (standard deviation of 1.7% points on a dry mass basis) and bulk density, which in turn affects the feed rate due to the applied volumetric dosing (standard deviation of 0.6 kg h^{-1}).

2.3. Char agglomeration

The dimensions, stamp pressure and mixture of the char agglomerates with water and binder were based on results of a preliminary study about agglomeration of gasifier coke for the electric arc furnace process [9]. The 5 cm diameter agglomerates were around 2 cm high and weighed about 50 g. The pressing pressure was 100 MPa. To achieve high stability and strength, the main compounds beside the char were 15% water and 24% molasses (as received mass basis). These shares do not necessarily represent optimum values for the specific case of wheat straw fast pyrolysis char [9]. The char agglomerates were produced with a discontinuous hydraulic stamp press (Losenhausenwerk AG). The maximum force of the stamp press is around 25 kN. Therefore this force is sufficient to cause a pressure of 100 MPa on the 5 cm diameter stamp. After reaching the target pressure, the position of the stamp was held for further 30 s.

The char fines were mixed with water and molasses for each agglomerate separately. The amount of water added was corrected by the moisture content of the char to achieve the desired mixture as described