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Grindability and combustion behavior of coal and torrefied biomass blends

M.V. Gil, R. García, C. Pevida, F. Rubiera *

Instituto Nacional del Carbón, INCAR-CSIC, Apartado 73, 33080 Oviedo, Spain

HIGHLIGHTS

- Biomass was treated by torrefaction before its co-combustion with coal.
- Biomass grindability was assessed from the particle size distribution after grinding.
- Torrefaction increased the proportion of small size fractions after grinding.
- Chestnut woodchips torrefied at 280 °C showed the best grindability characteristics.
- The addition of torrefied biomass reduced NO and SO_2 emissions during co-combustion.

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ABSTRACT

Biomass samples (pine, black poplar and chestnut woodchips) were torrefied to improve their grindability before being combusted in blends with coal. Torrefaction temperatures between 240 and 300 °C and residence times between 11 and 43 min were studied. The grindability of the torrefied biomass, evaluated from the particle size distribution of the ground sample, significantly improved compared to raw biomass. Higher temperatures increased the proportion of smaller-sized particles after grinding. Torrefied chestnut woodchips (280 °C, 22 min) showed the best grinding properties. This sample was blended with coal (5–55 wt.% biomass). The addition of torrefied biomass to coal up to 15 wt.% did not significantly increase the proportion of large-sized particles after grinding. No relevant differences in the burnout value were detected between the coal and coal/torrefied biomass blends due to the high reactivity of the coal. NO and SO_2 emissions decreased as the percentage of torrefied biomass in the blend with coal increased.

1. Introduction

Concerns about global warming due to the greenhouse effect over the last few decades, as well as worldwide policies aimed at reducing environmentally damaging gaseous emissions to achieve a sustainable energy model, suggest the need to seek alternative renewable energy sources that can complement or partially replace fossil fuels as the main energy source. In this regard, biomass appears to be a suitable feedstock due to its global energy generation potential together with its neutrality with respect to CO_2 emissions, its low NO_x and SO_2 emissions and its autonomy which will contribute to reducing dependence on foreign energy (García et al., 2012).

However, raw biomass, as a potential energy source, also has certain drawbacks, stemming from to its own nature. These include its heterogeneity and low energy density (García et al., 2013). Biomass is harder to grind due to its fibrous nature and so it is difficult to reduce to small homogeneous particles, which results in a low combustion efficiency (Bridgeman et al., 2008). These drawbacks affect its handling, transportation and storage, so they must be addressed before biomass can be considered as a realistic regular energy feedstock alternative. Torrefaction is widely considered as a promising pre-treatment for reducing some of these deficiencies, since it is known to improve the solid fuel properties of biomass (Bridgeman et al., 2010).

The process of torrefaction is defined as a thermal treatment under mild conditions, i.e., a temperature between 200 and 300 °C (Fisher et al., 2012) and a reaction time between 30 and 180 min (Shang et al., 2012) at atmospheric pressure (Nunes et al., 2014) in an inactive (Wannapeera et al., 2011) or O_2 impoverished atmosphere (3–6% O_2) (Wang et al., 2013) to avoid the spontaneous combustion of the treated fuel (Rousset et al., 2012). Under these conditions, a mild pyrolysis takes place, during

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* Corresponding author. Tel.: +34 985 118 975; fax: +34 985 297 662.
E-mail address: frubiera@incar.csic.es (F. Rubiera).

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which moisture is removed and between 20% to 75% of hemicellulose is converted into organic acids and low molecular weight volatile compounds (Chang et al., 2012), while structural lignin and cellulose are barely affected. The torrefaction process therefore involves several changes to the structure of the feedstock that affect some of its characteristics (Chen et al., 2015). A dry and partially carbonized solid that has a higher energy density on a mass basis is formed (Bridgeman et al., 2010). As the light volatiles are released, the percentage of carbon mass experiences a relative increase with respect to the hydrogen and oxygen contents (Bridgeman et al., 2010), which, in turn, causes an around 9–12% increase in the higher heating value (HHV) of the biomass (Bridgeman et al., 2008; Keipi et al., 2014).

The Hardgrove Grindability Index (HGI) is the most common grindability test for coals. HGI is an indicator to check the grinding scale of coal for a coal mill and represents the difficulty for grinding the solid sample into the powder. Higher HGI value means that the sample is easier to grind into powder. After torrefaction, HGI of the samples is usually improved (Wu et al., 2012), conferring optimum grinding and pelletizing properties on the biomass (Arias et al., 2008). In this way, the energy consumption during the processing of torrefied biomass can be reduced by 40–88% compared to the treatment of raw biomass (Tapasvi et al., 2012). Bridgeman et al. (2010) in an experimental investigation of the pulverization behavior of torrefied biomass concluded that the HGI of torrefied samples was not a reliable indicator of grindability performance for some biomass samples. However, the particle size distribution of the entire ground sample provided a more satisfactory basis for analyzing grinding behavior of biomass samples. These authors also suggested that, since grindability was improved with the torrefaction process, it was possible that biomass could be ground with coal at increased co-grinding rates. This is a matter of some importance, since the co-grinding of both fuels would avoid the need for a separate biomass feed system and lead to a reduction in costs.

The torrefaction process provides an opportunity to increase the bulk density of the biomass by densification, which increases the homogeneity and density of the biomass almost to the level of those of coal (Du et al., 2014). This has a favorable effect on the biomass properties involved in the supply chain (transport, storage and feeding) since an easy-to-fluidize, low-hydrophobic (Stelte et al., 2013), not-prone-to-agglomerate and high-energy density (up to 30% more than that of raw biomass) feedstock is obtained (Sarvaramini et al., 2013). Thus, when the biomass is co-fired with coal in existing power stations separate handling facilities are not required (Bridgeman et al., 2008). All the benefits indicated above, which are provided by the torrefaction of biomass, justify the extra energy consumption that occurs during the process. These improved characteristics, and the low CO_2 emissions that characterize biomass-based fuels, make torrefied biomass a promising feedstock for co-firing with pulverized coal in heating and power plants (Batidzirai et al., 2013). Thus, the co-combustion of biomass and coal becomes a cost-effective and efficient sustainable option for introducing renewable fuels into the energy system.

Torrefaction has received a great deal of attention in recent years. Most of the published research studies have focused on the compositional changes that occur in the raw samples during the process, as determined by proximate and ultimate analyses, on the mass loss during the biomass torrefaction and on the effect that the process conditions have on the chemical properties of the torrefied samples (Bridgeman et al., 2008; Chang et al., 2012; Keipi et al., 2014; Rousset et al., 2012; Wannapeera et al., 2011; Wu et al., 2012). However, few studies have been reported in the literature on the improvement of biomass grindability properties as a result of torrefaction or on the combustion properties of torrefied biomass (Arias et al., 2008; Bridgeman et al., 2010; Chen et al., 2011; Phanphanich and Mani, 2011). An improvement in the grindability characteristics is expected after the torrefaction process, but the chemistry of torrefaction is also influenced by the biomass composition, which means that the local available biomass resources should be investigated in order to evaluate the feasibility of torrefaction in a particular region (Tapasvi et al., 2012).

In Spain, the co-firing of biomass in coal-fired power stations is not at present a common practice, despite the wide availability of biomass wastes, such as forest residues. Some drawbacks need to be overcome in practice for introducing torrefied biomass in coal facilities, such as that the equipment designed to burn coal should be able to easily use biomass as well, or a stable and cheap flow of biomass is needed to sustain a biomass co-firing system. The costs of biomass acquisition and transportation will determine to a large extent the economic feasibility of co-firing. Furthermore, Chen et al. (2012) highlighted that, although a number of studies on the biomass torrefaction process have been carried out in recent years, the research on the combustibility and burning characteristics of torrefied biomass is insufficient. A more exhaustive research focused on the application of the torrefied biomass needs to be therefore performed, i.e., on the co-milling and co-firing of torrefied biomass and coal, since they have been hardly considered in the literature. In light of these deficiencies, the aim of this work is to study the grindability and combustion properties of blends of coal and torrefied biomass. Torrefied biomass samples from pine, black poplar and chestnut woodchips were obtained in a tubular rotary furnace under conditions of different torrefaction temperature (240, 260, 280 and 300 °C) and residence time (11, 22 and 43 min) in order to select the best biomass for use in co-combustion experiments with coal. The biomass was chosen on the basis of particle size distribution after grinding, since this parameter allows the grinding characteristics of the torrefied biomass samples to be compared. Both the grinding properties and the co-combustion behavior of coal/torrefied biomass blends were then studied. The burning performance of the blends was evaluated in an entrained flow reactor (EFR).

2. Methods

2.1. Fuel analysis

Three raw biomasses were used in the torrefaction experiments: pine (PIN), black poplar (POP) and chestnut (CHE) woodchips. The particle size of the biomass samples used in torrefaction was <8 mm. A high-volatile bituminous coal (COAL) was used in the coal/biomass blend evaluation. The biomass samples were provided by Pellets Asturias, S.L., while the coal sample was supplied by EDP Spain. The data obtained from the ultimate and proximate analyses together with the higher heating values (HHV) of the raw biomass and coal samples are shown in Table 1. The proximate analysis was performed according to the standard tests CEN/TS 14775, CEN/TS 14774-3 and CEN/TS 15148 for moisture, volatile matter (VM) content and ash content, respectively. The fixed carbon (FC) was calculated by difference. The ultimate analysis was performed using a LECO CHN 2000 elemental analyzer to determine the C, N and H mass percentages and a LECO S 114DR to determine the S content, while the O content was calculated by difference. The HHV of the samples was determined using an IKA C4000 calorimetric pump.

2.2. Torrefaction

Known amounts of the three biomass samples (350–450 g) were torrefied at different temperatures (240, 260, 280 and 300 °C) for a residence time of 22 min under nitrogen flow. In