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Oxy-fuel combustion of coal and biomass blends

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ABSTRACT

The ignition temperature, burnout and NO emissions of blends of a semi-anthracite and a high-volatile bituminous coal with 10 and 20 wt.% of olive waste were studied under oxy-fuel combustion conditions in an entrained flow reactor (EFR). The results obtained under several oxy-fuel atmospheres (21%O_2–79% CO_2, 30%O_2–70%CO_2 and 35%O_2–65%CO_2) were compared with those attained in air. The results indicated that replacing N_2 by CO_2 in the combustion atmosphere with 21% of O_2 caused an increase in the temperature of ignition and a decrease in the burnout value. When the O_2 concentration was increased to 30 and 35%, the temperature of ignition was lower and the burnout value was higher than in air conditions. A significant reduction in ignition temperature and a slight increase in the burnout value was observed after the addition of biomass, this trend becoming more noticeable as the biomass concentration was increased. The emissions of NO during oxy-fuel combustion were lower than under air-firing. However, they remained similar under all the oxy-fuel atmospheres with increasing O_2 concentrations. Emissions of NO were significantly reduced by the addition of biomass to the bituminous coal, although this effect was less noticeable in the case of the semi-anthracite.

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1. Introduction

The role of coal as an energy source has attracted renewed interest due to the stability of its supply and its relatively low cost, which will probably guarantee its inclusion in the energy mix in the foreseeable future [1]. Until renewable energy sources can reliably produce significant amounts of energy, the immediate energy demand is likely to be met by conventional fossil fuel combustion, such as coal. However, coal combustion produces a large amount of CO_2, which is the chief contributor to global climate change. To meet future targets for the reduction of greenhouse gas (GHG) emissions, CO_2 must be captured and stored. Several strategies for the reduction and capture of CO_2 from large-scale stationary power plants are currently being studied.

The oxy-fuel combustion of coal with recycled flue gas is considered as a promising option to ensure the continued use of coal for electric power production [2–5]. Conventional pf coal-fired boilers use air for combustion and the nitrogen in the air (approximately 79% by volume) has the effect of diluting the concentration of CO_2 in the flue gas, which is present in concentrations of 14–16% in air-firing conditions. However, during oxy-fuel combustion, fuel is burnt in a mixture of oxygen and recycled flue gas to yield a rich CO_2 (95%) and water vapour stream, which after purification and compression is ready for sequestration [6]. An important advantage of this technology is that it avoids the formation of thermal NO_x due to the absence of nitrogen gas in the combustion atmosphere, with the result that NO_x emissions are reduced. The amount of NO_x released also decreases because the NO_x in the recycled flue gas decomposes as it comes into contact with the flame-generated hydrocarbons and the reducing atmosphere near the flame, a mechanism to which Scheffknecht et al. [7] attach considerable importance.

In addition, the oxy-combustion of coal makes it possible to capture and sequester carbon using technology already available in conventional pulverized coal boilers, and to capitalize on the enormous quantities of money invested in existing boilers. What is more, oxy-fuel recycle combustion requires only a slight modification of the existing pulverized coal combustion technology that has already demonstrated its reliability and won widespread industrial acceptance [5].

The combustion of coal in the O_2/CO_2 atmosphere of an oxy-coal combustion boiler may be expected to be different to that of an O_2/N_2 atmosphere of a conventional coal-air combustion boiler, because the CO_2 gas is denser and has a higher specific heat capacity than N_2 and because coal may be gasified by the CO_2. Consequently, the replacement of N_2 by CO_2 will decrease the speed of propagation and stability of the flame and gas temperature, while increasing the unburned carbon content. It is for this reason that a high oxygen concentration in an oxy-fuel combustion atmosphere (up to approximately 30%) is generally used in order to match the combustion performance achieved in air in relation to

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flame temperature, ignition time, heat transfer, gas temperature profile and char burnout.

On the other hand, biomass is a renewable fuel which can be used to reduce CO_2 emissions. This source of energy is considered carbon neutral because the carbon dioxide released during its combustion is recycled as an integral part of the carbon cycle. The co-firing of biomass with coal is an environmentally friendly method of coal utilization since it reduces harmful emissions and provides an alternative to land filling [8]. One of the main advantages of co-firing biomass and coal is its relatively easy and cheap application in existing pulverized coal power plants, that requires only minor modifications compared to the costly construction of new biomass-only fired power plants [9]. The combination of oxy-fuel combustion with biomass could afford a method of disposal for CO_2 that has only partially been studied. Preliminary works have been carried out employing thermogravimetric analysis [8,10] and an entrained flow reactor [11] with the aim of studying the co-firing of coal and biomass under oxy-fuel conditions, but more research is required in order to introduce this practise at industrial scale.

In this work, a biomass derived from the olive oil production process, olive waste (OW), was utilized. It is the wet solid waste that remains after the process of pressing and extraction of the olive oil. The objective was to study the co-firing of coal with this biomass under oxy-fuel combustion conditions in an entrained flow reactor. Air conditions were used for comparison. The ignition temperature, burnout and NO emissions from various coal/biomass blends under air and oxy-fuel environments were determined and, in this way, the effect of adding biomass upon the oxy-fuel combustion of coal was evaluated.

2. Materials and methods

2.1. Materials

Two coals of different rank were used in this work: a semi-anthracite from the Hullera Vasco-Leonesa in León (Spain), HVN, and a South African high-volatile bituminous coal from the Aboño power plant in Asturias (Spain), SAB. A biomass, olive waste (OW), was also employed. The coal and biomass samples were ground and sieved to obtain a particle size fraction of 75–150 μm. The proximate and ultimate analyses together with the higher heating values of the samples are presented in Table 1.

Table 1
Proximate and ultimate analyses and higher heating value of the fuel samples.

Sample	HVN	SAB	OW
Origin	Spain	South Africa	Spain
Rank	sa	hvb	–
Proximate Analysis[a]			
Moisture content (wt.%)	1.1	2.4	9.2
Ash (wt.%, db)	10.7	15.0	7.6
V.M. (wt.%, db)	9.2	29.9	71.9
F.C. (wt.%, db)[b]	80.1	55.1	20.5
Ultimate Analysis (wt.%, daf)[a]			
C	91.7	81.5	54.3
H	3.5	5.0	6.6
N	1.9	2.1	1.9
S	1.6	0.9	0.2
O[b]	1.3	10.5	37.0
Higher heating value (MJ/kg, db)	31.8	27.8	19.9

sa: semi-anthracite; hvb: high-volatile bituminous coal. db: dry basis; daf: dry and ash free bases.
[a] The proximate analysis was conducted in a LECO TGA-601, and the ultimate analysis in a LECO CHNS-932.
[b] Calculated by difference.

2.2. Experimental device and procedure

The ignition and oxy-fuel combustion characteristics of the coals and coal/biomass blends at high heating rates and short residence times were studied in an entrained flow reactor (EFR), which has been described in detail elsewhere [12,13]. Briefly, the reactor has a reaction zone of length 1400 mm and internal diameter 40 mm which is electrically heated and is capable of reaching a maximum temperature of 1100 °C. Fuel samples are fed in from a hopper through an air-cooled injector to ensure that the temperature does not exceed 100 °C before entering the reaction zone and the mass flow is controlled by means of a mechanical feeding system. The gases are preheated to the oven temperature before being introduced into the reactor through flow straighteners. The flow rates of N_2, CO_2 and O_2 from the gas cylinders are controlled by mass flow controllers. A water-cooled collecting probe is inserted into the reaction chamber from below. Nitrogen is introduced at the top of this probe to quench the reaction products. Particles are removed by means of a cyclone and a filter, and the exhaust gases are monitored using a battery of analysers (O_2, CO_2, CO, NO and SO_2).

During the ignition tests carried out in the present study, the reactor was heated at 15 °C min^{-1} from 400 to 800 °C. The gas flow used in the tests ensured a particle residence time of 2.5 s at 500 °C, and excess oxygen (defined as the O_2 supplied in excess of that required for the stoichiometric combustion of coal) was set at a value of 25%. The criterion for determining the ignition temperature was based on the first derivative temperature curves of the gases produced. The ignition temperature was taken as the temperature at which the first derivative temperature curve, normalized by the maximum derivative value, reached a value of 10% [14].

On the other hand, the combustion tests were carried out at a reaction temperature of 1000 °C employing a particle residence time of 2.5 s. In order to check the constant gas temperature over the reactor height, a temperature profile along the reactor was measured with a fine wire type K thermocouple, while the gas was flowing, and it was found to be 1000 ± 10 °C. Burnout is defined as the loss of mass of a fuel during its combustion and is expressed as the ratio of mass loss during combustion to the total mass in the input coal. Fuel mass loss during the experiments was determined by the ash tracer method. The experimental errors in the burnout and NO measurements were 4 and 5% respectively.

Four binary mixtures of O_2/N_2 and O_2/CO_2 were employed to study the combustion behaviour of the coals and coal/biomass blends. Thus, for the ignition and combustion tests, air (21%O_2–79% N_2) was taken as reference and three binary mixtures of O_2 and CO_2 were compared: 21%O_2–79%CO_2, 30%O_2–70%CO_2 and 35%O_2–65% CO_2. The addition of 10 and 20 wt.% of olive waste to the coals was evaluated for all of the air and the oxy-fuel combustion atmospheres, in order to study the effect of adding biomass on the ignition temperature, burnout value and NO emissions.

3. Results and discussion

3.1. Ignition temperature

The ignition temperature of the semi-anthracite HVN and the bituminous coal SAB, as well as their blends with OW, under the different atmospheres studied is presented in Fig. 1. Both coals showed the same behaviour in relation to the combustion atmosphere. However, the ignition of the HVN coal took place at much higher temperatures than that of the SAB coal in all of the atmospheres studied, in accordance with its rank (Table 1). The reactivity of the high-volatile bituminous coal, SAB, is greater than that of the

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