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Full Length Article

# Oxy-fuel combustion study of biomass fuels in a 20 $kW_{th}$ fluidized bed combustor

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ABSTRACT

Oxy-fuel combustion is one of the promising carbon capture technologies considered to be suitable for future commercial applications with stationary combustion plants. Although more and more biomass and waste are now being burned in stationary combustion plants, research on oxy-fuel combustion of biomass has received much less attention in comparison to oxy-fuel combustion of coal. In this work, a series of tests was carried out in a 20 $kW_{th}$ fluidized bed combustor under oxy-fuel conditions firing two non-woody fuels (miscanthus and straw pellets) and one woody fuel (domestic wood pellet). The effects of the combustion atmosphere (air and oxy-fuel) and oxygen concentration in the oxidant of the oxy-fuel combustion on gas emissions and temperature profiles were systematically studied with the overall excess oxygen coefficient in the combustor being maintained roughly constant throughout the tests. The experimental results showed that replacing the air with an oxy-fuel oxidant of 21 vol% $O_2$ and 79 vol% $CO_2$ resulted in a significant decrease in combustion temperature and ultimately led to the extinction of the biomass flame due to the larger specific heat of $CO_2$ compared to $N_2$. To keep a similar temperature profile to that achieved under the air combustion conditions, the oxygen concentration in the oxidant of $O_2/CO_2$ mixture had to be increased to 30 vol%. A drastic decrease in CO emissions was observed for all three biomass fuels (up to 80% reduction when firing straw) under oxy-fuel combustion conditions providing that the oxygen concentration in the oxidant of $O_2/CO_2$ mixture was above 25 vol%. NOx emissions were found to decrease with the oxygen concentration in the oxy-fuel oxidant, due to i) the increase of bed temperature, which implies more volatile-N released and converted in the dense bed zone and ii) the less dilution of the gases inside the dense bed zone, which leads to a higher CO concentration in this region enhancing the reduction of NOx. Similar NOx emissions to those obtained with air combustion were found when the oxygen concentration in the oxy-fuel oxidant was kept at 30 vol%. Further analysis of the experimental results showed that the gas emissions when firing the non-woody fuels were controlled mainly by the freeboard temperature instead of the dense bed region temperature due to the characteristically high volatile matter content and fines of this kind of biomass fuels.

## 1. Introduction

Growing concerns on the greenhouse gas emissions and their potential impact on climate change demand not only the application of $CO_2$ capture and storage (CCS) technologies to large point anthropogenic $CO_2$ emission sources such as coal and natural gas fired power plants but also the implementation of $CO_2$ negative combustion technologies such as Bio-energy with Carbon Capture and Storage (BECCS) within the next decades. Although removing $CO_2$ from the atmosphere, i.e. direct capture of $CO_2$ from air, may be necessary in the longer term, direct $CO_2$ capture is more technically challenging and more expensive than CCS and BECCS applied to large scale combustion plants [1–3]. Biomass is considered as a renewable fuel, a carbon-neutral energy source and hence its combustion integrated with CCS can lead to negative $CO_2$ emissions. Biomass has already captured worldwide attention in the context of greenhouse gas control even though fossil fuels are expected to retain their dominant role in the world energy supply in the coming decades [4].

Oxy-fuel combustion is one of the most developed CCS technologies and considered as technically feasible and economically competitive for future commercial applications [5–7]. Oxy-fuel combustion refers to fuel being burned in a mixture of oxygen and recycled flue gas (RFG). Unlike conventional air combustion plants that use air as the oxidant, an oxy-fired plant employs an Air Separation Unit (ASU) to produce an almost pure oxygen stream. The oxygen stream is then combined with RFG to produce an oxygen enriched gas as the oxidant. The flue gas

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recycle is necessary to moderate the otherwise excessively high flame temperature that would result from fuel combustion in pure oxygen. After the removal of water and other impurities from the flue gas exhaust stream, high-purity $CO_2$ (up to 95%) is produced and almost ready for sequestration [8,9]. As mentioned above, the combination of oxy-fuel combustion with biomass could effectively provide a method which would not only avoid further $CO_2$ emissions but also helps reduce the atmospheric $CO_2$. Furthermore, the oxy-fuel process also offers other advantages such as improving the ignition and burnout performance.

Among all the available combustion technologies, fluidized bed combustion (FBC) is often considered as the best choice for the combustion and/or co-combustion of biomass, waste and other low quality solid fuels due to its fuel flexibility, long residence times, and uniform combustion temperatures. The characteristics of FBC also offers several advantages for its application in oxy-fuel systems [10]. Firstly, the difficulty of flue gas recirculation for temperature control in pulverized fuel (PF) applications could be reduced in circulating fluidized bed (CFB) by means of the bed material recirculation, since the specific heat of the solids is much higher than that of the recycled flue gas. Secondly, lower NOx emissions and better sulphur removal are possible. Finally, it is easier to retrofit a fluidized bed boiler from air to oxy-fuel combustion as there will be no need for a new burner.

The effects of oxy-fuel atmosphere and $O_2$ concentration in the oxy-fuel oxidant gas on pollutant emissions (NOx and CO) in fluidized bed systems firing different kinds of coal have been thoroughly investigated during the past years by a number of researchers. In general, the experimental results showed that NOx emissions in oxy-fuel combustion with low $O_2$ concentrations are lower than those obtained under air-firing atmosphere, because of the lower temperatures as well as higher char and CO concentrations in the dense bed [10,11]. Furthermore, NOx emissions were found to increase with the increasing $O_2$ concentrations in the oxy-fuel oxidant, which is as a result of i) the increase of the temperature in the furnace which elevates the concentrations of O and OH radicals and enhances NO formation and ii) the lower gas velocity in the riser and longer residence time of fuel particles in the combustor, which may promote the fuel-N conversion into NOx precursors [10–14]. In some studies an opposite trend was found, i.e. an decrease of NOx with the increasing $O_2$ concentration in the oxy-fuel oxidant, as in the work of de las Obras-Loscertales et al. [15]. The authors explained this trend by means of the different operational procedure used, comparing with other investigations: in their work [15], an increase in the oxygen concentration was compensated with an increase of the coal flow rate fed to the reactor, keeping constant the total gas flow rate and excess oxygen coefficient in all tests. As a result, more unconverted char was present in the bed, favouring the NO reduction on the char surface.

Regarding CO emissions, Duan et al. [16] observed a much lower CO emission in air than those in an oxy-fuel atmosphere with the same $O_2$ concentration when firing two kind of coal in a 50 $kW_{th}$ CFB facility, due to the higher temperature achieved under the air combustion conditions. They also reported a decrease in CO emissions when the $O_2$ concentration in the oxy-fuel oxidant gas increased; as the oxidation of carbon was more complete and therefore less CO was formed. On the other hand, Hofbauer et al. [14] observed similar CO emissions for air combustion and two oxy-fuel cases investigated (with 26 vol% and 36 vol% of $O_2$ in the oxidant, respectively), firing bituminous coal in a 150 $kW_{th}$ CFB reactor. Jia et al. [17] performed a series of oxy-fuel tests with flue gas recycle in a 100 $kW_{th}$ CFB combustor firing bituminous coal. The CO emissions of oxy-fuel combustion were found to be equal or slightly lower than those of air firing, mainly due to the higher cyclone temperature achieved with oxy-fuel combustion.

Biomass properties differ from those of coal in many important ways which results in different combustion behaviours [18]. For example, biomass generally has less carbon, more oxygen, higher hydrogen content and lower heating value. There are huge differences in volatile matter contents between biomass and coal: biomass can lose up to 90% of their masses (as volatiles) in its first stage of combustion, much higher than any ranks of coal (from less than 10% for anthracite to ca. 40% for high-volatile bituminous coals) [19,20]. The effects of oxy-fuel combustion conditions on the combustion performance and emissions of biomass fuels are expected to be differing from those of coal as a result of the differences in properties between biomass and coal. So far, few have investigated oxy-fuel combustion in fluidized bed reactors firing 100% biomass fuels and therefore further research is still needed. Duan et al. [21] conducted a series of experiments firing three kinds of Chinese biomass fuels, i.e. rice husk, wood chips and dry wood flour, under air and oxy-fuel atmosphere in a 10 $kW_{th}$ CFB combustor. The main objective of their study was to investigate the pollutant emissions of the co-firing of biomass with coal under oxy-fuel combustion conditions although experiments firing only the biomass fuels were also carried out for comparison purposes. They observed lower NO emissions in the oxy-fuel atmosphere compared with those with air combustion. This behaviour was explained as the result of the reduced yield of NOx precursors like $NH_3$ during the devolatilization process and the enhanced NO reductions via char/NO/CO reactions under the oxy-fuel combustion conditions. They also concluded that the NO emission increased with the bed temperature, overall oxygen concentration and the primary oxidant fraction when co-firing biomass and coal with a mixing ratio of 0.2 in oxy-fuel combustion. However, the effects of the oxygen concentration in the oxy-fuel oxidant gas on the gas emissions and temperature profiles firing 100% biomass fuels were not investigated in this study.

The objective of the present work is to continue delving into the barely-studied oxy-fuel combustion of biomass fuels firing three kind of biomass fuels, two non-woody (miscanthus and straw) and one woody (wood), in a 20 $kW_{th}$ bubbling fluidized bed (BFB) combustor, studying the effects of the combustion atmosphere (air and oxy-fuel) and the oxygen concentration in the oxy-fuel oxidant on the gas emissions and temperature profiles.

## 2. Experimental

### *2.1. Experimental setup*

The experimental system, shown in Fig. 1, mainly includes a BFB combustor (20 $kW_{th}$) and the auxiliary systems for air supply, biomass feeding, and gas analysis. The stainless steel combustor consists of a bed zone of 102 mm i.d. and 800 mm height, a freeboard of 154 mm i.d. and 1100 mm height, and a plenum of 102 mm i.d. and 300 mm height. A water cooled heat extraction probe located inside the combustor allows the bed temperature to be controlled by means of the extraction of heat from the combustor. This probe can be moved vertically along the combustor to change the contact surface inside the combustor to prevent the bed from reaching very high temperature values and thus avoid agglomeration and defluidisation of the bed particles. Furthermore, the cooling water flow rate of the probe can be adjusted to control the heat extraction and hence the combustion temperature inside the combustor.

As the real flue gas recirculation is not included with the experimental system, a premixed flow of $CO_2$ and $O_2$ which are supplied from gas cylinders and monitored by rota meters (calibrated for $O_2$ and $CO_2$ respectively) is used as the main oxidant for the oxy-fuel combustion and is also used as the fluidizing gas of the BFB combustor. For the conventional air combustion tests, compressed air is used as the main oxidant and fluidizing gas. The air flow rate is monitored by a rotameter that is calibrated for air. For both oxy and air combustion tests, a small flow of compressed air is also fed through the biomass feeder hopper to prevent backfire and to stop the sand particles coming into the feeding pipe. The oxidant gas is mainly fed into the combustor through the plenum and a porous stainless gas distribution plate with 100 μm pore size and 12 mm thickness. An electric air pre-heater before the plenum