Co-firing of Coal/Biomass in a Pilot Scale Oxy-Combustor: Experiences and Experimental Results

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Air-firing of the fossil fuels results to relatively low concentration of CO_2 in flue gases which make the capture of CO_2 difficult and expensive. Oxy-firing combustion is a novel method of using enriched oxygen for coal/biomass combustion with Recycled Flue Gases (RFG) to control the adiabatic flame temperature and to increase the CO_2 concentration of the off-gases up to a 60-70% oxy-firing mode (compared to air-fired mode, around 12-14%). This new technology is being applied at Cranfield University to retrofit an existing 100kWth air-firing combustor to the oxy-firing mode. This paper presents the procedure of the modifications applied on the combustor and the excellent results obtained for co-firing of pulverised coal and biomass in this rig.

Keywords Oxy-Coal Combustion; Recycled Flue Gas (RFG); Carbon Capture Sequestration (CCS); Gaseous Emissions

1. Introduction

Oxy-fuel combustion is one of the main options being considered for the capture of CO_2 from fossil fuel-fired power generation. There is an essential needed to satisfy the current regulations regarding reduction of greenhouse emissions mainly by implementation of the carbon capture and storage (CCS) technologies. The main carbon capture techniques are as follows: pre-combustion, post combustion, Oxy-fuel combustion and Other emerging technologies: chemical looping combustion, membrane separation, carbonation- calcinations cycles, etc.

Oxy-fuel combustion has several characteristics which make it a very attractive technology to implement to both: existing air-firing and new power plants. Among the main advantages are:

- The smaller size of the flue gas conditioning equipment (e.g. electrostatic precipitator or desulphurisation), which is situated downstream of the furnace. The decrease in the size needed has a direct effect on the capital costs, which are shorter.
- Generation of a current of flue gas with high percentage of CO_2, avoiding the elevated operation costs of post-combustion technologies where large amounts of chemical absorbent have to be replaced periodically.
- As there is no necessities of extensive additional spaces to place the carbon capture equipment in oxy-fuel combustion, this technology can be put into practice with more ease than others (e.g. pre-combustion or post-combustion) to existing power plants.

There has been recently a good attention to the research projects on the oxyfuel combustion. A good summery report on the oxyfuel combustion of pulverised coal with recycled flue gas is published by IEAGEG [1]. Ignition, combustion and heat transfer, the recycle ratio as well as gas emission and ash deposition aspect are studied in some references [2, 3, 4, 5, 6, 7, and 8]. However, more investigations on co-firing of coal and biomass under oxy-combustion conditions are required for the aforementioned topics [2, 3]. This paper presents the procedure of the modifications applied on an air-firing combustor to convert it to oxy-firing mode and the promising results obtained for co-firing of pulverised coal and biomass in this rig.

2. Experimental setup

2.1 Retrofitting process

A 100 kWth combustion rig at the Centre for Energy and Resource Technology (CERT) in Cranfield University is being converted to an oxy-firing combustor. This is to study the oxyfuel combustion technology by determining the process environment and impact on ash behaviour and material corrosion at different fuel and load conditions. The retrofitting process tasks have taken place in three phases. The first phase was focused on the design and installation of the recirculation line. For this, it was necessary to set up the recirculation fan, the oxygen injection to the recycle flue gas (secondary oxygen) and the trace heating wiring. The latter has the goal of preventing condensation of water in flue gas recirculation lines. Additionally, in this stage a line to supply the carbon dioxide was installed to convey the pulverised fuel from the hopper to the burner itself.

The second phase covered several tasks, the design and fitting of an axial swirler in the air inlet port of the burner; the implementation of a gas tight fan to recirculate the flue gas; the primary oxygen injection, added to the stream in charge of conveying the fuel to the combustor; installation of the gas tight fuel feed hopper; and, the design and replacement of a new carbon dioxide line supply, to give response to the design requirements of the new fuel feeder.

The third phase is in progress. Among the changes planned to take place during this stage are the incorporation of the dry recycled flue gas into the process (taking into account SO_x and water vapour removal from the flue gas). This aims to achieve the maximum concentration of CO_2 in the exhaust (>90%) through the dry basis recirculation of the flue gases. The installation of a system to measure the acid dew point in the recycled flue gas (CAPCIS system) and implementation of a heat transfer measurement system and also design a procedure to measure the content of burnout are going to be the last phase of the modifications.

The general flow diagram the Cranfield oxyfuel burner rig showing the performed and ongoing modifications is shown in Fig.1.

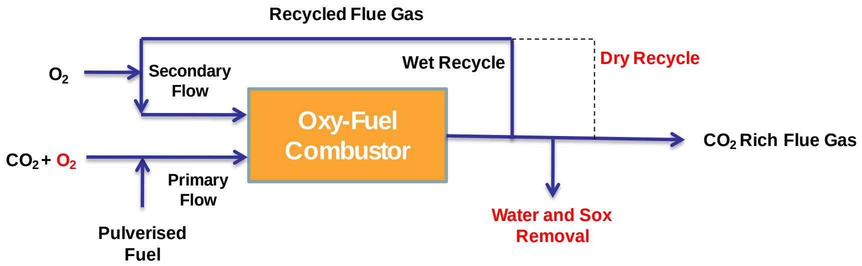

Fig.1: Flow diagram of the Cranfield oxy-fired pulverised fuel combustor (red: ongoing modifications)

2.2 Methodology

The multi-fuel combustor rig at the Centre of Energy and Resource Technology (CERT) at Cranfield University is composed of a fluidised bed (50 kW_{th}) and a pulverised fuel combustor (100 kW_{th}). For the oxy-combustion tests only the pulverised fuel combustor (PF) is used. The zone belonging to the fluidised bed (FB) is used during the preheating of the chamber, prior to the actual oxy-combustion test. Once the combustor is heated above 500°C the gate valve, which is between the FB and the PF, needs to be closed (Fig. 2).

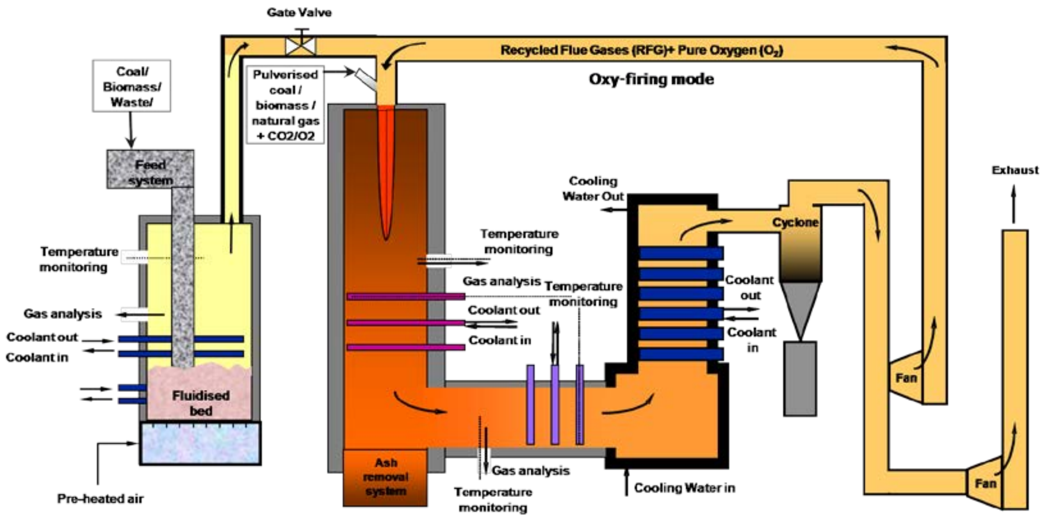

Fig. 2 Diagram of the Multi-fuel Combustion Rig at CERT.

The pulverised fuel is fed to the oxy-combustor at a constant rate using a fuel feeder provided by a metering screw, a vibratory tray and a Venturi eductor. Additionally, the feeder has several purge points, where CO_2 is injected, so to avoid the air ingress into the hopper. Once the pulverised fuel is at the Venturi eductor, it is going to be fluidised towards the burner entry by a pure CO_2 gas stream coming from the CO_2 cylinders. Prior to feeding this stream to the burner, the primary oxygen supplied from pure oxygen cylinders, is injected.

The burner is provided by a pilot flame port and a flame detector. The pulverised fuel is burnt through the vertical section. This section has several view ports and temperature sensors are located at different locations of the rig. These sensors are type K thermocouples and the data acquisition system is a Pico Logger Unit-TC-08. The acquired temperature data are also registered using the aforementioned data logger. At the bottom of the vertical section of the chamber sampling probes are located. Three of these ports are used by the deposition probes. Once the test has finished, it is necessary to leave the chamber to cool down for about 18 to 24 hours before the ash deposition probes can be taken out for sample collection and analyses using a Scanning Electron Microscope (SEM). An on-line high resolution multi-component Fourier Transform Infra-red (FTIR) gas analyser is connected to a gas analysis probe trough a chamber port to study the composition of the oxy-combustion flue gases.

The exhaust gas passes through two water-cooled heat exchangers, one in the horizontal and one in the vertical section, before exiting from the oxy-combustor. After leaving the chamber, the gas is led to a cyclone where the suspension particles are removed. From there, part of the gas is recirculated to the chamber and the rest is emitted to the atmosphere. The pipelines that conduct the recycled flue gas are thermally isolated and equipped by a trace heating system to avoid the temperature drop of the flue gas below the acid dew point. The secondary oxygen is injected into this stream prior to feed it to the oxy-combustor.

2.3 Experimental conditions

The pulverised fuel used was 100% Daw Mill Coal, 100% El Cerrejon Coal, 100% Cereal Co-Product Biomass (CCP), and, a blends of 50% Daw Mill Coal and 50% CCP. Table 1 shows the analysis for the different types of fuel used for the experiments in the oxy-combustor facility at CERT in Cranfield University.

The percentage of recycle flue gas was maintained between 50% and 55% of the total flue gas exiting the oxy-combustor. For the oxygen injection, in the primary stream, the one that is in charge of conveying the pulverised fuel up to the burner, the maximum oxygen limit permitted was 21 % (v/v). For the secondary stream, which is mainly made up of the recycled flue gas, the upper limit for the content of oxygen was 28% (v/v). The operation pressure in the chamber must be below the atmospheric pressure due to the design conditions. However, to minimise the air ingress into the process, the pressure during the experimental tests was kept as close as possible to the atmospheric pressure.

Table 1 Analysis of Daw Mill Coal, El Cerrejon Coal and Cereal Co-Product Biomass (CCP).

	Daw Mill Coal	**El Cerrejon Coal**	**Cereal Co-Product (CCP)**
Moisture % (w/w) (total)	4.6	7.0	8.1
Ash, %(w/w) (as received)	4.2	9.0	4.2
Volatile Matter, % (w/w) (as received)	31.3	34.8	70.8
CV, kJ/kg (as received)			
Gross	25260	27850	17610
Net	24107	26700	16340
C%(w/w) (as received)	0.7415	0.6920	0.433
O%(w/w) (as received)	0.0438	0.0440	0.058
H%(w/w) (as received)	0.1049	0.0998	0.3557
Ash			
SiO_2	36.8	60.69	44.36
Al_2O_3	23.9	22.01	2.79
Fe_2O_3	11.2	7.43	2.47
CaO	12	2.27	7.78
MgO	2.5	2.90	3.96
K_2O	0.5	2.32	24.72
Na_2O	1.5	1.06	0.36
TiO_2	1.1	0.92	0.12
BaO		0.11	0.05
Mn_3O_4	0.4	0.06	0.10
P_2O_5		**0.21**	**12.04**

3. Results and Discussion

Experimental tests have been carried out in the retrofitted combustor using different types of fuels (coal, biomass and blends of the parent fuels). These tests have taken place after finishing each of the aforementioned phases in the retrofitting process section.

The experimental results after performing the first stage of the modifications, showed an average of about 35% CO_2 and 15% H_2O concentration in the flue gases in oxy-firing mode, using 100% coal as fuel. The low percentage of carbon dioxide reached was a clear sign of air ingress into the system. Additionally, the burning process was not steady and the flame was found to be not intense enough and detached from fuel nozzle.

The results after the second phase revealed a remarkable improvement in the performance of the oxy-combustor. The enhancement of the operation could be seen, firstly, from the much higher stability achieved during the tests as a direct effect of the new fuel feeder installation. With the previous fuel feeder, the main problem was due to its small capacity (only enough to supply fuel for around 30 minutes). Consequently, every time during a refilling process there was considerable air ingress into the process, making a noticeable drop in the concentration of carbon dioxide. Fig. 3-a shows this effect, where the yellow line tells the time instants when the refilling of the feeder were done. Fig. 3-b shows the performance with the new fuel feeder and second phase of modifications in the rig, a very stable operation is reached.

Table 2 presents the experimental data obtained through the latest tests performed, with regard to the maximum CO2 percentage achieved, and the percentage for the rest of the gaseous species at those conditions. It is also shown the maximum temperatures reached for each of the experiments.

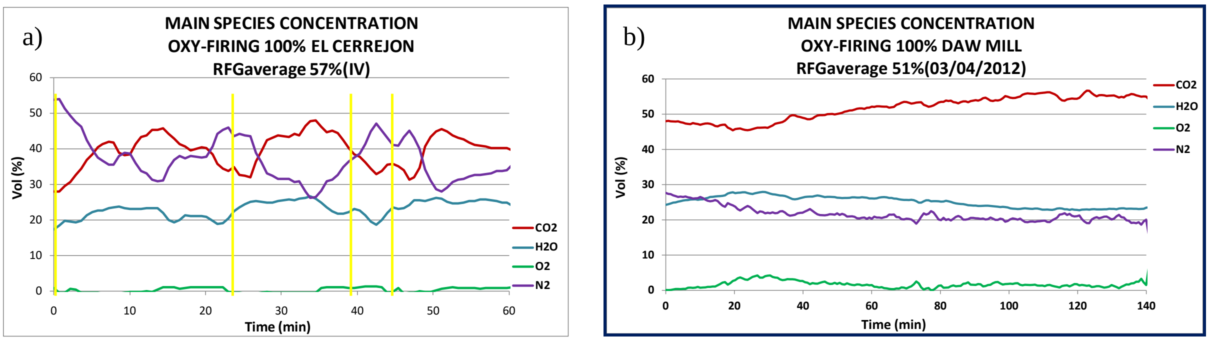

Fig. 3 Comparison in the oxy-combustor behaviour after performing a) the 1st phase of modifications, and, b) the 2nd phase of the modifications

Table 2 Experimental results after the modifications made in the second phase.

	100% Daw Mill	**50% Daw Mill- 50% CCP**	**100% Cereal Co-Product (CCP)**
Gas Composition			
CO_2 (%) (w.b.)	56.67	53.02	45.71
H_2O (%) (w.b.)	22.98	25.46	29.60
O_2 (%) (w.b.)	1.26	1.78	2.94
SO_2 ppm	2589	1217	47
CO ppm	543	400	1026
HCl ppm	359	355	52
NO ppm	399	262	94
NO_2 ppm	14	14	2
Maximum Temperatures (ºC)	**1100**	**994**	**848**

By comparing the gas compositions of the flue gas generated using different fuels, it is found that the maximum percentage of carbon dioxide is achieved when 100% coal is burnt. For the content of water vapour, there is a gradual increase when the content of biomass in the fuel is higher. Considering the presence of SO_2 in the flue gas, there is a dramatic decrease of this specie as the percentage of biomass in the fuel is risen. On the other hand, from the analysis of the results regarding the CO, there is no trend, as in the case of 100% biomass, there is an unexpected increase. This fact contradicts the theoretical prediction since the coal has a higher content of carbon than the biomass, as it can be seen in Table 1. Comparing the temperatures, a trend to reach a higher temperature, can be observed where there is more presence of coal in the fuel.

Fig. 4 shows the comparison between the ashes generated and deposited on the probes when using different types of fuels.

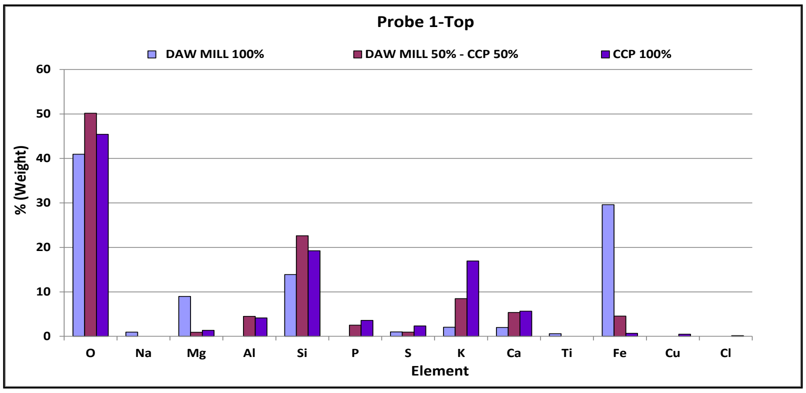

Fig. 4 Results from SEM analysis of ashes from different fuels.

Different behaviours can be observed by analysing Fig. 4. There are elements that follow the trend marked by the previous analysis of the ash, shown in Table 1: iron and titanium percentages increased with the percentage of coal, and the presence of potassium rose in ashes with the percentage of biomass. On the other hand, oxygen, silicon, and magnesium do not follow a clear pattern. An opposite trend from the expected is seen for the content of calcium in ashes.

2.Conclusions

A number of modifications have been carried out on an air-firing multi-fuel combustor rig at the Centre of Energy and Resource Technology (CERT) in Cranfield University to convert it into an oxy-combustor. These changes have taken place in three phases, being the last one in progress.

Experiments have been accomplished using different types of fuels: 100% Coal, 100% CCP biomass, and 50% coal-50% CCP, maintaining the percentage of recycled flue gas between 50 and 55%. The results generated during the latest tests showed a maximum in the concentration of CO_2 in the flue gas of 57% (w.b.) and the temperatures in the oxy-combustor reached 1100ºC, when 100% coal was used. This shows a successful retrofitting process of the burner to the oxyfuel mode. It was observed that the maximum percentage of carbon dioxide is reached when 100% coal is burnt and there was a gradual increase in water vapour a dramatic decrease of SO_2 in the flue gas when the content of biomass in the fuel is higher.

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