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COMMISSIONING OF A 0.8 MW_{TH} CFBC FOR OXY-FUEL COMBUSTION

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ABSTRACT

Oxy-fuel fluidized bed combustion (FBC) is a new technology being developed for power production from carbonaceous fuels while producing a nearly pure stream of CO₂ ready for sequestration or storage. Unlike oxy-fuel pulverized fuel combustion technology, oxy-fuel FBC offers the opportunity to use poor quality coals, hydrocarbon residues and a range of other materials including biomass. In Canada, pitches, tars and bottoms, in particular, are available in large quantities in western Canada, and this technology offers an opportunity to deal with many of these waste feedstocks in an environmentally benign manner. In addition, oxy-fuel circulating FBC (CFBC) can be fired at lower flue gas recycle ratio, offering potentially smaller plants for any given power output, and can capture sulphur *in situ*.

CanmetENERGY has been operating a 75 kW oxy-fuel CFBC since 2006 with full flue gas recycle. Initial results were very encouraging and in order to further study oxy-fuel FBC technology, a 0.8 MW_{th} CFBC unit has been retrofitted for oxy-fuel research. The facility is used to emulate commercial oxy-fuel CFBC performance. The modifications included adding oxygen supply, flue gas recycle train, airtight fly ash discharge, flue gas compressor for baghouse pulsing and system purge, *etc.*, as well as upgrading the control and instrumentation for oxy-firing. The most major challenge has been to properly seal the entire CFBC unit to prevent air ingress.

Fuels fired during the commissioning phase included bituminous coal and petroleum coke from the US, and lignite from Saskatchewan. Combustion under oxy-fuel conditions has proved to be very stable and the transition from air firing mode to oxy-fuel firing mode and *vice versa* were quick and presented little operational difficulties. This work has demonstrated that the retrofitted oxy-fuel CFBC can produce a stream of flue gas containing 80% to 90% CO₂. The NO_x emissions were significantly lower compared to air firing in CFBC with the same fuel. SO₂ capture was in the range of 70% to 75%, but limestone utilization is lower than in air-firing mode, and research is on-going to better understand sulphation under oxy-firing conditions.

INTRODUCTION

Anthropogenic CO₂ production is primarily driven by fossil fuel combustion. To reduce greenhouse gas emissions from fossil fuel combustion in the electric utility industry, CO₂ capture and storage (CCS) appears to be among the most promising methods (1). Oxy-fuel pulverized coal combustion technology had been studied for many years (1, 2, 3). The commissioning of a 30 MW_{th} oxy-fuel demonstration plant at Schwarze Pumpe in Germany by Vattenfall is an important milestone for the

development of pulverized fuel (PF) oxy-fuel technology. The Schwarze Pumpe oxy-fuel plant has been running initial tests since mid 2008 (4).

Oxy-fuel circulating fluidized bed combustion (CFBC) is a relatively new technology compared with oxy-fuel PF combustion, but has several advantages. It can be fired at lower flue gas recycle ratio; it can capture sulphur *in situ*; and can co-fire biomass. CanmetENERGY-Ottawa has been working on this technology since 2006, using a 75 kW_{th} CFBC facility with full flue gas recycle and has obtained very positive results (5, 6). Eriksson *et al.* (7) have also reported on their initial oxy-fuel CFBC results in 2007 using a similar facility to that at CanmetENERGY and their results also confirm the same advantages with the technology. At this point the technology is receiving attention in Canada (5, 6), Finland (7), Poland (8), China (9), USA (10) and Spain, where a 20 MW_{th} demonstration oxy-fuel CFBC plant is being built (11), among other countries.

In order to advance studies in this area, a 0.8 MW_{th} CFBC unit at CanmetENERGY has been retrofitted for oxy-fuel research. The facility is used to simulate commercial oxy-fuel CFBC performance. The modifications included adding oxygen supply, flue gas recycle train, airtight fly ash discharge, flue gas compressor for baghouse pulsing and system purge, *etc.*, as well as upgrading the control and instrumentation for oxy-firing. This paper describes the pilot oxy-fuel CFBC plant and initial results obtained during the commissioning of the unit.

CanmetENERGY's 0.8 MW_{th} OXY-FUEL CFBC

The 0.8 MW_{th} pilot-scale CFBC research facility at CanmetENERGY was built in the 1990s to generate a database useful for the design and process optimization of full-scale units, study emissions of pollutants and predict the combustion performance of feed stocks. The main components of the facility comprise the refractory-lined combustor and cyclone, an inclined L-valve, four retractable bayonet-type cooling tubes, flue gas cooler, baghouse, fuel and sorbent feed system, stack and air supply system. The combustor has an inside diameter of 0.406 m and an internal height of 6.5 m. The CFBC has comprehensive instrumentation, control and data acquisition systems and is also equipped with an 0.5 MW start-up burner fired with natural gas to preheat the unit as well as to provide an additional heat source if needed.

Modifications to the pilot-scale CFBC began in 2007 for oxy-fuel CFBC research. Oxygen supply and flue gas recycle were installed, and much work related to preventing leakage throughout the entire plant has been undertaken. The oxy-fuel CFBC is shown schematically in Fig. 1. Components shown in red are the existing parts, and components shown in blue are the new additions. The primary fluidizing gas, secondary gas and loop gas are all supplied from the main gas header. The supply pressure of the main gas header is typically maintained at 55 kPag. Secondary gas may be introduced into the combustor at up to 5 different locations along the height of the combustor. The positions of these inlets are at 765 mm, 1549 mm, 2159 mm, 2769 mm and 4521 mm above the distributor.

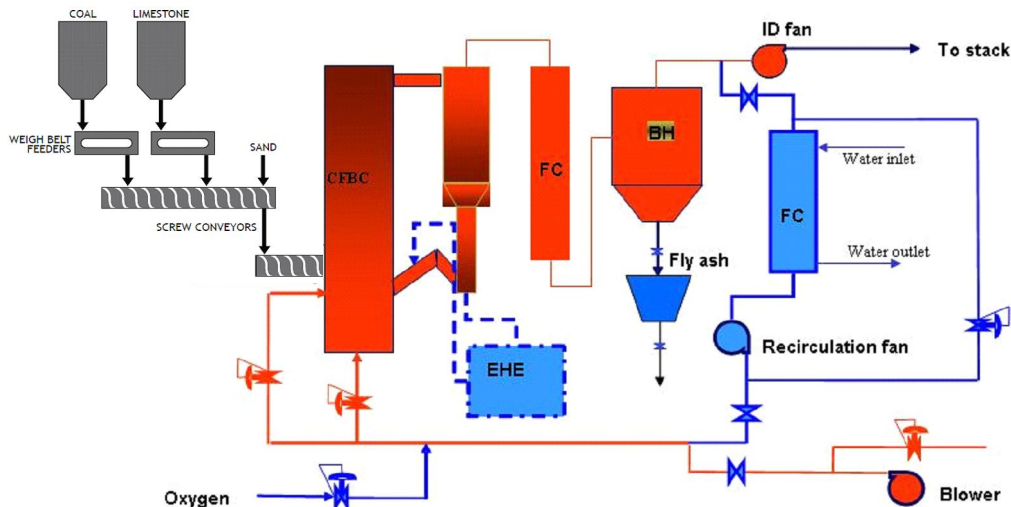


Figure 1. CanmetENERGY 0.8 MW_{th} oxy-fuel CFBC research facility

The recycled flue gas is controlled using a Tuthill Competitor GT series tri-lobe blower capable of delivering up to 800 kg/h of recycled flue gas through the main air header at a discharge pressure of 55 kPa. The flow, temperature and header pressure of recycled flue gas are measured and logged. Oxygen is added to the main header after the loop seal gas header. Oxidant level in the gas header can be brought up to 29% oxygen (vol. wet basis). Oxidant level in the main air header is measured with a Siemens Oxymat 61. The Oxymat 61 measures oxygen using the paramagnetic alternating pressure method. Both the primary and secondary gases have the same oxidant level at the present time. A planned upgrade will see a second oxygen train installed, allowing the primary and secondary fluidizing gases to be operated at different oxygen levels if desired.

Oxygen for the enrichment of the recycled flue gas is provided from a Linde-supplied 1500 US gal. bulk liquid oxygen tank. The oxygen is vaporized and brought to the pilot facility at 50 psig. The maximum design flow of oxygen using this system is 220 kg/h. Isolation between the air system and recycle gas system is achieved using two pneumatically actuated proportionate slide gate valves.

The fuel feeding system is comprised of a fuel storage bin, vibratory bin dispenser and belt-type gravimetric weigh feeder. The maximum feed rate of the weigh feeder is 342 kg/h with a 20:1 turndown ratio.

The sorbent feeding system has a similar arrangement as the fuel system. Maximum sorbent feed rate is 64.8 kg/h.

The combustor is equipped with four bayonet cooling tubes that can be inserted or raised during operation. Each bayonet tube is 7160 mm in length and is fabricated with a 30 mm schedule 40 outer tube and a 16 mm 18 BWG inner tube (both 304SS). The bayonet tubes were designed for a total heat duty of 546 kW with a water flow rate of 217 L/min.

Fly ash removal is accomplished with a negative pressure fabric filter dust collector with a pulse jet bag cleaning system. The dust collector uses Nomex bags with

maximum temperature rating of 200°C. The design gas volume is 0.59 Am³/s with a normal operation inlet temperature of 177°C and a dust loading of 48-79 g/Am³.

Ports are available for solid and gas sampling from the combustor. In addition, CanmetENERGY has the equipment and trained staff for stack sampling of volatile organic compounds (VOCs) and isokinetic sampling for semi-volatile organic compounds (SVOCs), metals and polyaromatic hydrocarbons (PAHs) using US EPA or Environment Canada standard sampling techniques.

Under air firing conditions, the pressure balance point is usually at the furnace exit. Under oxy-fuel mode, the combustor is run under slightly positive pressure to prevent air ingress. Some typical operating parameter ranges are shown in Table 1.

Table 1. Range of operating conditions

Input	Range
Combustion temperature	up to 980°C
Heat input	up to 0.8 MW _{th}
Excess O ₂	2-10%
Ca/S molar ratio	0-3
Primary air	30-100%
Secondary air	0-70%
Loop seal air	1-5%
Superficial velocity	2-7 m/s
O ₂ in primary gas	up to 29%
O ₂ in secondary gas	up to 29%

Table 2. Fuel analysis, wt% (as analyzed)

	Petroleum coke	Anthracite
Proximate analysis		
Moisture	0.63	8.3
Ash	0.48	30.7
Volatile	10.17	6.4
Fixed carbon	88.72	
Ultimate analysis		
Carbon	86.84	54.6
Hydrogen	3.42	1.7
Nitrogen	1.48	0.9
Sulphur	5.61	1.0
Oxygen (diff)	1.59	2.8
LHV, MJ/kg	32.46	19.89

COMMISSIONING TESTS

Bituminous coal, lignite, petroleum coke and anthracite were all used in the commissioning tests. Table 2 gives analysis of some of the fuels. Limestone was not used in the first several tests since the primary goal was to first obtain the desired CO₂ levels in the flue gas. In later tests, Calpo limestone (98.6% CaCO₃) from Canada was used.

The first several tests under oxy-fuel mode revealed that transition from air firing to oxy-fuel firing was quick and smooth. The transition took less than 30 min to complete. Combustion under oxy-fuel mode was stable. Transition from oxy-fuel to air firing mode was faster. No operational difficulties were encountered. However, CO₂ concentrations in the flue gas were only about 50-60% in these initial tests. Repeated efforts were made to seal the flue gas recycle train and all components which are under negative pressure during oxy-fuel operation (baghouse, flue gas cooler, etc.). It was a very difficult task. Once the system was properly sealed, CO₂ concentration in the flue gas reached ~85%+ consistently in the following tests.

Figures 2 and 3 show the first successful oxy-fuel test in the 0.8 MW_{th} CFBC unit firing Pine Bend coke. CO₂ concentration remained at ~90% for the entire duration of the oxy-fuel firing period. Temperature distribution along the axis of the combustor was similar to that of air firing with the same fuel. Figure 2 shows the transition from air to oxy-fuel firing was completed in about 30 min, and the transition from oxy-fuel to air firing was very fast indeed. Figure 3 shows the concentrations of SO₂ and CO. Note the SO₂ concentration was over the range of the SO₂ analyzer (1.5%) during oxy-fuel firing conditions. Later a new analyzer with a much higher range was purchased and installed. CO concentration was about the same for both air firing and oxy-fuel firing periods. The increase of CO at time 16+ h was apparently caused by the decrease of oxygen concentration as shown in Fig. 2.

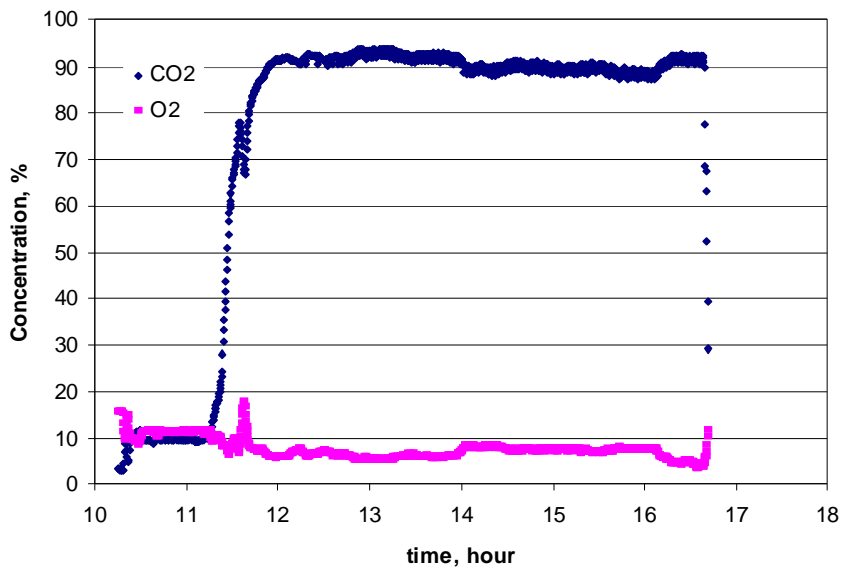


Figure 2. Oxy-fuel combustion of Pine Bend coke. Note the transition from air firing to oxy-fuel mode in about 30 min.

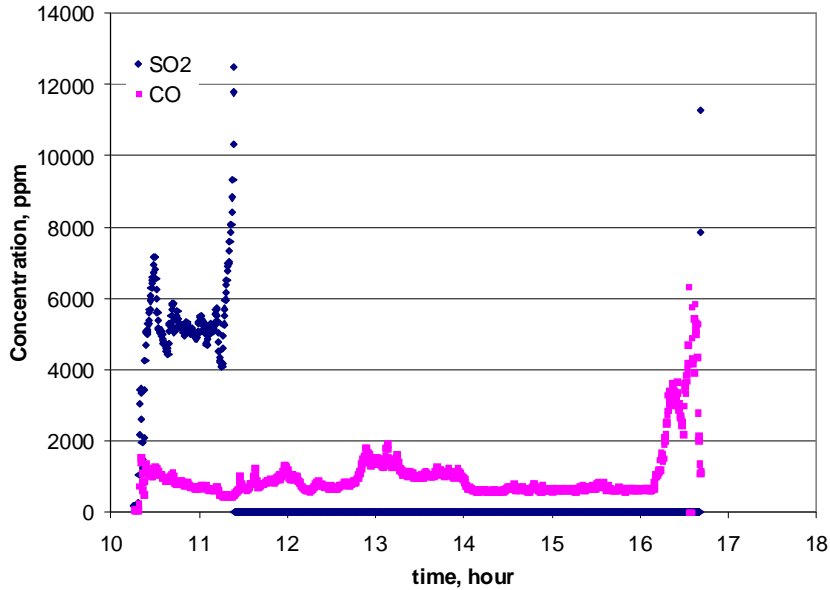


Figure 3. SO₂ and CO concentrations during oxy-fuel combustion of Pine Bend coke.

As the commissioning process progressed, a full week test using anthracite with limestone addition was carried out. Figure 4 shows CO₂ and O₂ concentrations for the entire duration of the test.

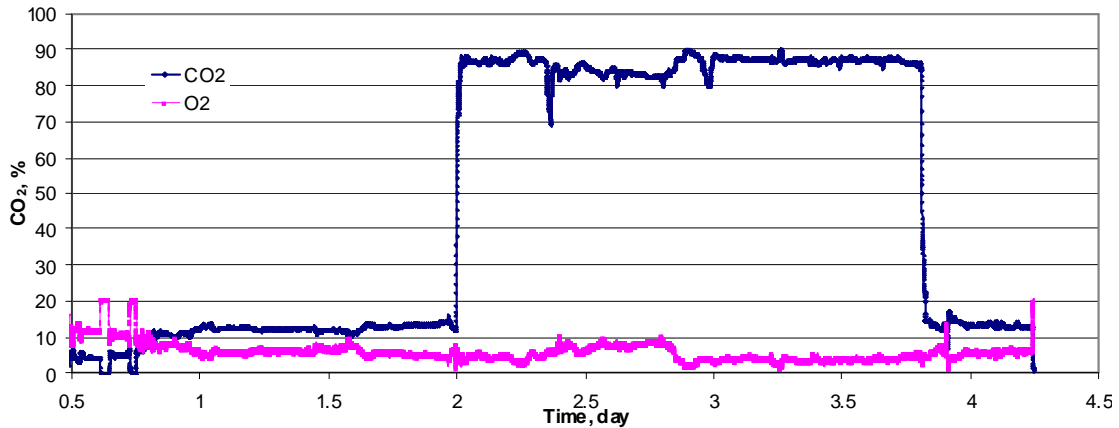


Figure 4. Oxy-fuel CFBC combustion of anthracite.

Results shown in Fig. 4 and Table 3 demonstrate that the retrofitted 0.8 MW_{th} oxy-fuel CFBC unit was reliable. It was extremely stable during operation. This test proved it can be run continuously for long periods of time under oxy-fuel CFBC conditions to generate useful data for industrial purposes. It should be noted that since the pilot CFBC does not have an ash cooler (external or integrated) in the return loop, the recycle ratio was higher, at 70.7%. Fuel nitrogen to NO was low, 1.13% under oxy-fuel conditions. However, it is in line with our earlier results on the much smaller 10 cm (75 kW_{th}) oxy-fuel mini-CFBC plant (5, 6). Sulphur capture was poorer than would be expected based on experience with air firing. This poor performance may also have been exacerbated by the fact that the limestone used was too fine. It is of interest that Scala and Salatino (12) also noted a lower degree of sulphation in batch tests carried out in a 40 mm ID oxy-fired bubbling bed reactor,

which they relate to the well known phenomenon that direct sulphation is slower than indirect sulphation until conversions reach a level around 30-40% (13). However, a complicating factor is that all comparative evidence for this difference has been developed using TGA and differential reactors using dry gas mixtures (14). However, while it is recognized that direct sulphation is influenced by water (15), the assumption that indirect sulphation is not itself strongly influenced by water is not well founded (16). Therefore, while sulphation in oxy-fuel FBC systems needs further study, the evidence for the superiority of conversions achieved by direct sulphation, for longer sulphation periods is not supported by these results, and needs to be reassessed with tests carried out with water levels typical of combustion (10-20%).

Table 3. Oxy-fuel CFBC combustion of anthracite at nominal temperature of 900°C

	Anthracite
Average freeboard temperature, °C	905.5 ± 37
Fuel, kg/h	96.5 ± 1.4
Limestone, kg/h	9.5 ± 1
Oxygen, kg/h	138.7 ± 4
Nominal Ca/S	3
O ₂ , %	3.85 ± 0.55
CO ₂ , %	86.9 ± 0.6
CO, ppm	1143 ± 300
SO ₂ , ppm	2628 ± 592
NO, ppm	108.4 ± 14
Superficial velocity in riser, m/s	5.9±0.4
Recycle ratio, %	70.7 ± 5
Sulphur capture, %	43.8 ± 4
Fuel N to NO, %	1.13 ± 0.1

CONCLUSIONS

A 0.8 MW_{th} pilot-scale CFBC unit at CanmetENERGY had been successfully retrofitted for oxy-fuel CFBC research. The unit can fire a wide range of fuels including coal, petroleum coke and lignite. The operation of oxy-fuel CFBC was stable and reliable. Transition from air firing to oxy-fuel firing was fast and smooth. CO₂ concentrations in the flue gas reached 85%+ during the entire oxy-fuel firing period. NO emissions were extremely low with only 1.13% fuel nitrogen converted to NO. Sulphur capture was poorer in the initial series of commissioning tests. Part of the reason may have been that the limestone used was too fine.

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