OXY-FUEL COMBUSTION

At the CANMET Vertical Combustor Research Facility

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ABSTRACT

The CANMET Energy Technology Center is a division of Natural Resources Canada and undertakes primary research and technology development activities for the benefit of Canadians and a wide range of external clients.

The Vertical Combustor Research Facility (VCRF) was built in 1994 and is CANMET's most modern pilot facility for combustion research. The facility is capable of firing pulverized coal and or natural gas using air or oxygen. It is one of the few research facilities operating in the world that can fire pulverized coal in a mixture of recycled flue gases and oxygen in order to simulate O_2/CO_2 combustion techniques. These combustion techniques can be used to enrich the concentration of CO_2 in the products of combustion of fossil-fueled power plants in order to facilitate the capture of CO_2 for use and or sequestration.

This paper outlines and discusses the performance of a proprietary O_2/CO_2 burner that has been developed at CANMET. Computational Fluid Dynamic (CFD) case studies will be used to illustrate our present understanding of the strengths and weaknesses of this burner design. Finally, future research work planned in this area will be described.

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1.0 INTRODUCTION

A strategic research program aimed at capturing CO_2 from large central utility scale electricity generating plants is underway at the CANMET Energy Technology Center, a division of Natural Resources Canada. This effort began in 1993 with the planning and construction of a unique pilot scale facility located at CANMET's facilities in Ottawa, Canada.

The Vertical Combustor Research Facility (VCRF) has been in continuous operation since it was commissioned in late 1994. This facility is capable of firing pulverised coal and/or natural gas under conditions approximating those found in industrial situations. The unit is capable of firing rates up to 0.3 MWth and features generous access provisions to probe the flame envelope.

A pre-competitive research program arranged in co-operation with an international consortium of private and public sector partners has been the main mechanism used for operating the facility. The focus of this program has been to study the use of oxygen in the combustion of pulverized coal in order to enrich the CO_2 content of the flue gases produced (Croiset *et. al*., 1998, Thambimuthu *et. al*., 1998, Croiset *et. al*., 1999, Croiset *et. al*., 2000). This elegant combustion technique can produce flue gases approaching 98 % CO_2 (by vol, dry basis) illustrating the potential of this combustion based approach to facilitate the recovery of CO_2 for use and/or sequestration.

A major element of the research program since 1997 has been to develop a computational fluid dynamics (CFD) modelling capability to complement the pilot-scale experimental investigations. The opportunity to validate the CFD models with data from the facility assures that the predictive capabilities developed can be applied towards technology development and scale-up activities with confidence.

Another major element of the research program since 1999 has been to develop a process modelling capability to better understand how oxy-fuel techniques can best be applied in retrofit situations (Zheng *et. al*., 2001, Singh *et. al*., 2001).

In 2000 significant changes were made to the VCRF to study the integrated treatment of pollutants, which is highly complementary to the oxy-fuel investigations (Mortazavi *et. al*., 2001).

This paper will describe the current configuration of the pilot scale combustion facility and provide an overview of the CFD activities to date. The existing burner operational envelope will be described and selected results will be used to explain the CFD modeling approach used to simulate the combustion within the VCRF. Finally, future research work in the area of oxy-fuel combustion will be described.

2.0 PILOT PLANT CONFIGURATION

Figure 1 provides a schematic of the current pilot plant configuration.

There are four major systems associated with the VCRF. They are the fuel delivery system, the combustion system, the flue gas treatment system and the instrumentation and control system, which are described briefly below.

There are also several other systems of importance to the operation of the VCRF including: coal crushing, drying and blending facilities, on-site bulk vessels provided by Air Liquide Canada for the storage of oxygen and carbon dioxide and finally, a gas detection/alarm system for monitoring the environment within the building housing the VCRF.

2.1 Fuel Delivery System

Crushed and dried coal is fed to a single pulverizer operated in batch mode to prepare approximately 12 hours worth of fuel. Ambient air is used to sweep the mill and entrain the pulverized product to an overhead storage silo. This silo feeds a loss-in-mass-feeder which is capable of maintaining a relatively steady flow of coal to an eductor assembly. Ambient air or carbon dioxide from the bulk storage vessel is used as the primary stream, depending on the experiment, to deliver the coal to the burner front. Recent modifications have been made to allow oxygen to be mixed into the primary stream in order to study what impact this oxygen has on NO formation in the near burner region; however this feature was not used for the work reported in this paper.

2.2 Combustion System

The combustion takes place in a vertically down fired combustor that has an inside diameter of 60 cm and an overall length of 8.3 m. The combustor is refractory lined to conserve heat to provide a realistic time-temperature history for the burning particles of coal. The design of the combustor barrel is modular so that sections can be removed or added as necessary. Water cooled panels can be inserted in the lower sections to control the outlet flue gas temperature. A variety of access ports are provided along the length of the combustor to facilitate probing, especially within the flame region itself, as shown in Figure 2.

Standard IFRF probes are used for measuring radiation and sampling for species such as O_2, CO, CO_2, NO, NO_2 and SO_2. A proprietary high velocity shielded thermocouple probe is used to measure gas temperatures up to 1700 C. This temperature probe has been shown to withstand the severe environment imposed by firing coal at the high flame temperatures associated with oxygen enriched firing.

A single register, swirl stabilized burner developed at CANMET has been used for the work reported in this paper. This burner provides stable flames over a wide range of firing conditions and has been in constant service since the facility was commissioned. Figure 3 illustrates the arrangement of the burner.

Note the primary stream is admitted to an annulus located within the inner diameter of the swirling secondary stream. The secondary stream comprises ambient air alone or in combination with carbon dioxide from the bulk storage vessel, nitrogen, oxygen or recycled flue gases. The amount of oxygen mixed into the secondary stream is limited to 28 % (dry volume basis) for safety reasons. Most operating scenarios require some oxygen to be admitted directly at the burner and this is accomplished by a series of holes arranged in the annulus located within the inner diameter of the primary stream.

Natural gas is fired down the center of the burner and a small tertiary stream is provided for premixing the natural gas stream. The tertiary stream also provides a buffer between the gas and the oxygen stream to prevent excessive flame temperatures near the burner front. The resulting burner assembly does not require any water cooled parts. The swirl register is a movable block unit made of carbon steel.

2.3 Flue Gas Treatment System

Recent modifications have been made to the flue gas system to study the integrated treatment of pollutants. The new equipment is arranged in parallel with the existing baghouse, and consists of a new five field electrostatic precipitator (ESP) and a Condensing Heat Exchanger® (CHX).

The CHX was made available to CANMET in mid 2000 by McDermott Technologies Inc, and is similar to a unit located in their Alliance , Ohio research center. The CHX unit features Teflon coated gas side surfaces and is configured to inject liquid sorbents over the tubes to capture gaseous pollutants such as sulfur dioxide.

The ESP is a custom designed unit supplied by McGill Airclean Corporation in January 2001. It features active control of two field groupings which will facilitate on-line optimization for fine particulate capture.

The flue gas recirculation system has recently been modified to eliminate bottlenecks limiting the throughput and to simplify the fan arrangement. The dedicated recirculation fan has been eliminated and the flue gas recirculation stream is now taken from downstream of the induced draft (ID) fan. The ID fan now operates against a control valve to generate the pressure required by the recirculation system. The ID fan has also been provided with a variable frequency drive for better control.

2.4 Instrumentation and Controls

The main burner fires into a refractory quarl which incorporates a natural gas fired ignitor. This ignitor is monitored using an ultraviolet scanner. The coal flame is monitored using an infrared scanner.

The VCRF is provided with three Continuous Emissions Monitoring (CEM) systems to monitor conditions at the mixing plenum before the burner, the combustor exit and the ID fan inlet. Species measured include O_2, CO, CO_2, SO_2, NO and NO_2. An in-situ oxygen cell is used to ensure the oxygen content of the secondary stream is kept below 28 % (dry volume basis) for safety reasons.

System control and data acquisition is provided by a Honeywell series 9000 PLC with a dedicated PC supervisor. It receives real-time information from numerous primary elements and control devices and sends back active commands through interactive displays on a PC monitor located within the control room. This system allows the VCRF to be safely run by two operators.

3.0 BURNER OPERATIONAL ENVELOPE

Selected results from four experiments conducted using western sub-bituminous coal are presented below to illustrate the operational envelope of the existing burner design. The runs are designated WS-1, WS-3, WS-4, WS-5 and WS-7 and the key operational parameters are summarized in Table 1.

Table 1 – Operational Parameters

Trial Ref	Target Flue Gas CO_2 Content (dry vol. %)	Primary Gas	Secondary Gas	Excess CO_2 (1) (wt. %)	Total Flue Gas (2) (kg/hr)	Target Feed Gas (3) Composition (dry vol. %)		
						O_2	N_2	CO_2
WS-1	17	Air	Air	0	292	21	79	0
WS-4	25	Air	Air + O_2	0	224	28	72	0
WS-5	30	Air	Air + O_2 + CO_2	22	229	28	66	5
WS-7	70	Air	Air + O_2 + CO_2	184	271	28	27	45
WS-3	98	CO_2	Flue gas + O_2	211	238	35	0	65

Notes:

1) "excess CO_2" is defined as the mass of excess CO_2 leaving the combustion process relative to the mass of CO_2 produced in the combustion process.
2) "total flue gas" is defined as the total mass of flue gas exiting the combustion process.
3) "target feed gas" composition refers to the bulk gas mixture entering the burner.

WS-1 was performed in air and serves to establish baseline conditions.

Run WS-4 was performed using air for the primary stream while the secondary stream consisted of air enriched with oxygen in order to represent the classic case of “enriched air” combustion. Run WS-5 blended a small amount of bulk CO_2 into the secondary stream to achieve a target flue gas CO_2 concentration of 30 % (dry volume basis). Similarly, run WS-7 blended a large amount of bulk CO_2 into the secondary stream to achieve a target flue gas concentration of 70 % (dry volume basis). The concept of “excess CO_2” is introduced here to quantify the mass of excess CO_2 leaving the combustion process relative to the mass of CO_2 produced in the combustion process. This concept is similar to the concept of “excess oxygen” commonly used to quantify the amount of oxygen provided in excess of stoichiometric requirements. Runs WS-5 and WS-7 were intended to show how varying the quantity of “excess CO_2” can impact the flame characteristics and the CO_2 concentration in the products of combustion.

Run WS-3 represents the classic case of “O_2/CO_2 recycle combustion” where air is replaced by a mixture of O_2 and CO_2. Run WS-3 was performed using bulk CO_2 for the primary stream. The secondary stream consisted of recycled flue gases enriched with oxygen. Note that in real retrofit situations, recycled flue gases would likely be used in the primary stream to convey the coal to the burner.

A summary of the resulting burner mass flows is provided in Table 2.

Table 2 – Actual Mass Flows

Trial Ref	Coal Flow (kg/hr)	Pri. Gas (kg/hr)		Direct O_2 (kg/hr)	Secondary Gas (kg/hr)			
		Air	CO_2		O_2	Air	CO_2	Flue Gas
WS-1	35.5	59.0	-	-	-	209.5	-	-
WS-4	35.5	59.3		6.4	10.4	123.6	-	-
WS-5	35.5	59.0	-	9.6	11.9	107.8	16.3	-
WS-7	35.5	60.3	-	10.9	32.8	17.9	133.2	-
WS-3	35.5	-	59.0	32.5	24.4	-	20(1)	94.9

Notes:
1) This CO_2 was used for sealing/purging and was not injected through the burner

It is important to note that in all cases the oxygen enrichment in the secondary stream was maximized but limited to 28 % (dry volume basis) for safety reasons. This causes a more or less steady increase in the amount of oxygen directly injected to the burner from run WS-4 to WS-5 to WS-7 to WS-3. While run WS-3 was performed without oxygen enrichment of the primary stream, the VCRF is now capable of such operation. Enrichment of the primary stream with oxygen would decrease the amount of oxygen directly injected at the burner.

Each experiment was done with a target value of 2 % excess oxygen (dry volume basis). The secondary swirl was set at 8 for all experiments which corresponds to a calculated swirl number of approximately 1.05.

Table 3 summarizes key performance data for these experiments.

Table 3 - Performance Data

Trial ID	Calculated Adiabatic Flame Temperature (1) (°C)	Measured Peak Flame Temperature (2) (°C)	Measured Emissions (3) (ppm, dry basis)		Estimated Emissions (4) (ng/J)
			CO	NO	NO
WS-1	2100	1380	<10	710	236
WS-4	>2750	1565	35	1750	482
WS-5	2650	1565	35	1550	352
WS-7	2120	1440	60	1100	144
WS-3	2230	1440	75	1090	78

Notes:

1) calculated using HYSYS
2) measured using a proprietary shielded high velocity thermocouple probe
3) values shown are the average taken over the duration of each experiment and were measured in the flue gas leaving the combustion process.
4) values show were corrected to account for the reduced gas flow to the stack assuming that the "excess CO_2" would be provided by recycling flue gases

The operation of the burner is in large measure governed by the target value for the flame temperature. A theoretical adiabatic flame temperature can be calculated and compared to the actual peak flame temperature measured in the combustor. Despite the offset caused by combustor heat losses, the calculation of the theoretical adiabatic flame temperature provides a useful relationship for understanding the performance of the burner.

While oxygen enrichment can be used to increase flame temperatures, it is of little practical benefit in most pulverized coal fired boiler retrofit situations. A notable exception would be the use of oxygen enrichment to increase flame temperatures in slag tap furnace designs. Since the current focus of this work is on adapting oxy-fuel combustion techniques to existing dry bottom furnaces, great emphasis is placed on maintaining the flame temperature close to that in air. This approach maximizes the potential that the existing furnace heat balance and slagging behavior can at least be maintained, if not improved.

Referring to Table 3 it can be seen that experiments WS-7 and WS-3 were designed to produce flame temperatures closely approximating run WS-1, the baseline in air case. Note that run WS-3 requires slightly more oxygen in the feed gas (35 %) than Run WS-7 (28 %) in order to achieve the same measured flame temperature due to the higher proportion of CO_2 in the flue gases attained during run WS-3.

Runs WS-4 and WS-5 produce much higher flame temperatures than run WS-1, the baseline in air case. Runs WS-4 and WS-5 illustrate the great difficulty associated with elevated flame temperatures caused by oxygen enrichment of the feed gas to the burner without sufficient diluent in the form of bulk CO_2 or flue gas recycle.

Table 3 shows that in all four experiments, the combustion was stable with minimum CO production at very modest levels of excess oxygen.

It should be noted that the NO emissions for run WS-1, the baseline in air case, are relatively high because the existing burner does not incorporate any NO_x reducing strategies.

The resulting mass emission rates of NO (mass of NO per unit of heat input) were estimated assuming that the "excess CO_2" would be provided by recycling flue gases in any real situation. This approach allows the measured NO concentrations leaving the combustion process to be converted to an equitable basis for comparison.

Table 3 clearly shows that the mass emission rates of NO decrease as the amount of molecular nitrogen is decreased in the flame region, and that the highest NO emission occurs under conditions where molecular nitrogen is exposed to the highest flame temperatures. This finding can be understood in light of the tendency to form thermal NO_x when molecular nitrogen is exposed to regions of high temperature within the flame.

It is interesting to note the reduced mass emission rate of NO for run WS-3 as compared to run WS-7 despite the fact that both runs present the same NO concentration leaving the combustion process. This effect can be explained largely by the much reduced flue gas flow that would be discharged to the stack in the case of run WS-3. The fact that both runs present the same NO concentration leaving the combustion process illustrates the dominant role of thermal NO_x formation in enriched air combustion. Finally, one should also recall that NO is actually being recycled to the flame during run WS-3 presenting a possible mechanism for destruction of NO in fuel rich regions of the flame during O_2/CO_2 recycle combustion.

These findings point clearly to the influence that the flame characteristics can have on the formation of NO and these relationships are explored further in the following discussion on modeling.

4.0 CFD MODELING

Computational Fluid Dynamic (CFD) modeling techniques were applied to the VCRF in order to help understand how the combustion medium and the flame characteristics interact. The opportunity to validate the models by measuring species concentrations within the flame envelope provides confidence in interpreting the findings.

4.1 General Approach

The mathematical pulverized coal flame model used in this exercise is based on the work of Lockwood *et. al.* (1984, 88, 91). Model predictions are obtained by solving the time-averaged conservation equations for the gas and coal particle phases. The gas phase is treated in an Eulerian approach, but the particle phase is accounted for in a Lagrangian manner.

Coal particles of selected sizes are injected into the solution domain from firing locations. Each particle trajectory, statistically representative of a specific size group from a specific firing location, is tracked and its pyrolysis and combustion history is recorded. The flow/particle interactions are handled by the "particle source in cell" method (Migdal *et. al.*, 1967) where the exchanges in mass, momentum and energy between phases are handled by appropriate sink/source terms in the gas/particulate equations. The standard k-epsilon method is used for turbulent fluid flow calculations.

Pyrolysis is simulated by a first order single reaction model (Badzioch *et. al.*, 1970). Volatile combustion is assumed to be controlled by the mixing rate of reactants (the eddy-breakup model of Magnussen *et. al.*, 1976). Char burning is governed by the chemical kinetic rate and the external diffusion rate of oxygen to the char surface (Lockwood *et. al.*, 1984). The kinetic parameters for pyrolysis and char combustion were experimentally obtained prior to the CFD study.

NO_x formation is estimated by using a combination of probability density functions and the eddy-dissipation concept to predict thermal, prompt and fuel NO in turbulent coal flames (Chui *et. al.*, 1996). This approach of modelling coal combustion and NO_x formation characteristics in air has been successfully validated by CETC (Chui *et. al.*, 1997). The current study extends its application to a O_2/CO_2 medium. The model naturally adjusts to give the proper radiative properties of the new medium based on the concentrations of CO, H_2O and the substantially higher amount of CO_2. Also, the thermal and prompt NO_x formation mechanism is automatically de-activated in the absence of molecular nitrogen. The major assumption is that the devolatilization and char burning characteristics in an elevated CO_2 medium do not differ significantly from those in air. This assumption is currently being explored in collaboration with Sandia National Laboratories at Livermore in California using their unique experimental capabilities to determine kinetic coefficients for individual coal particles burning in atmospheres enriched in oxygen and/or carbon dioxide (Shaddix *et. al.*, 2001).

4.2 Special Considerations

To ensure a realistic simulation of the VCRF, the inlet fluid flow and coal particle characteristics at the burner face must first be properly determined. Figures 4 and 5 show the results of separate CFD studies conducted on the two components upstream of the burner exit: the swirl generator for the secondary gas and the coal delivery system for the primary gas stream.

An important finding was that the cyclone entrance chamber to the coal gun contributed a significant swirl to the coal particles and the carrier gas as they exited the front face of the burner (Figure 5). This spinning of the coal particles resulted in a non-uniform distribution of fuel at the burner exit and which in turn caused the flame to deviate significantly from the intended axi-symmetric behavior.

Figure 6 compares the predictions of NO_x along the furnace centreline with measured data for two CFD simulations of coal combustion in air. The first simulation assumed the flame characteristics to be axi-symmetric and did not model the flow through the coal delivery system. The resulting discrepancy between calculated and measured values was very large (dashed line and diamonds, Figure 6). The second simulation removed the axi-symmetric assumption, accounted for the swirl in coal particles through the coal delivery system and hence, brought the predicted NO_x much closer to the measured data (solid line and circles, Figure 6). This study concluded that the CFD model of the VCRF must include the swirl generator and the coal delivery system in order to properly capture the three-dimensional shape of the flame and correctly predict the NO_x formation characteristics.

4.3 O_2/CO_2 Recycle Combustion Results

The CFD modelling approach described above was tested on a variety of oxy-fuel combustion experiments to gain insights on the impact that the fluid dynamics and the properties of the combustion medium have on flame and pollutant formation characteristics. One such experiment represented the classic case of O_2/CO_2 recycle combustion where all of the combustion air is replaced with oxygen in order to achieve the maximum possible enrichment of CO_2 in the products of combustion. This experiment is designated WS-3 and was performed using a western sub-bituminous coal.

The burner was operated as outlined in Table 3. A value of 35 % oxygen in the bulk feed gas was set to match as closely as possible the flame temperature expected in air. The secondary stream consisted of recycled flue gases enriched with oxygen prior to admission to the swirl generator. The amount of recycle was then adjusted to its maximum. Since the safety limit was set at 28 % oxygen (dry volume basis) in the secondary stream and the primary stream consisted of pure CO_2 with no oxygen enrichment, the balance of the oxygen requirement was added directly at the burner.

This experimental set-up was essentially void of molecular nitrogen and capable of generating a very high concentration of CO_2 in the exhaust. The only molecular nitrogen present in the system was a result of infiltration of ambient air, which was minimised by operating the combustor at a slight positive pressure and sealing the openings with bulk CO_2. Figure 7 shows the temperature, oxygen and NO distributions across the mid-section of the combustor. Because of the way the oxygen was introduced through the burner, a high momentum flame was created with a high concentration of O_2 in its core, which enhanced the formation of NO. Evidence of this can be seen in Figure 7 where the resulting NO distribution closely follows the O_2 distribution. Figure 8 compares measured and predicted values of temperature and oxygen along the centre-line of the furnace. Considering the extreme difficulty in obtaining accurate measurements in this environment using intrusive probes, the agreement was quite good.

The mass emission rate of NO for the CFD simulation was estimated to be 63 ng/J and compared relatively well to the 78 ng/J estimate based on the experiment. The CFD simulation could actually account for the NO recycled through both the primary and secondary streams, illustrating the ability of the model to simulate what was not experimentally tested at the time because of the limitation of using bulk CO_2 (not recycled flue gases) to convey the coal.

In conclusion, the CFD simulations confirmed that the modelling technique predicted the correct trends over a wide range of conditions within the existing burner operating envelope.

5.0 ACCOMPLISHMENTS

The Vertical Combustor Research Facility has recently been upgraded to enhance it's capabilities to derive reliable experimental data for a variety of oxy-fuel combustion techniques as applied to pulverized coal firing for retrofit situations.

The existing burner design has been shown to operate in a stable manner over a very wide range of oxy-fuel operating conditions.

Computational fluid dynamic simulations have provided physical insights as to how the fluid dynamics and the combustion medium interact with pollutant formation characteristics, especially NO.

The use of experimental results to validate computational predictions has provided the confidence necessary to make improvements to the existing burner design.

6.0 FUTURE ACTIVITIES

The focus of research involving the Vertical Combustor Research Facility will remain to explore the science of oxy-fuel combustion techniques for fossil fuels.

The experimental program will be expanded to include other coal types and natural gas.

CANMET will continue to collaborate with SANDIA National Laboratories at Livermore California to better understand the role chemical kinetics play in predicting the combustion behavior of selected coals under oxy-fuel combustion conditions.

Modifications will be made to the existing burner to improve its performance, including specific attempts to provide a more symmetric coal distribution at the entrance to the burner and to refine the manner in which oxygen is admitted to the burner.

The results of this research will be used by CANMET and its partners to understand how best to apply oxy-fuel combustion techniques to existing power plants and subsequently to the design of new plants.

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The *CANMET* CO_2 *Consortium* retains all rights to this work for the benefit of its members and all reports are normally used in confidence to its members. This paper presents certain non-confidential findings and the conclusions do not necessarily reflect the view of the *CANMET* CO_2 *Consortium* or *PERD.*

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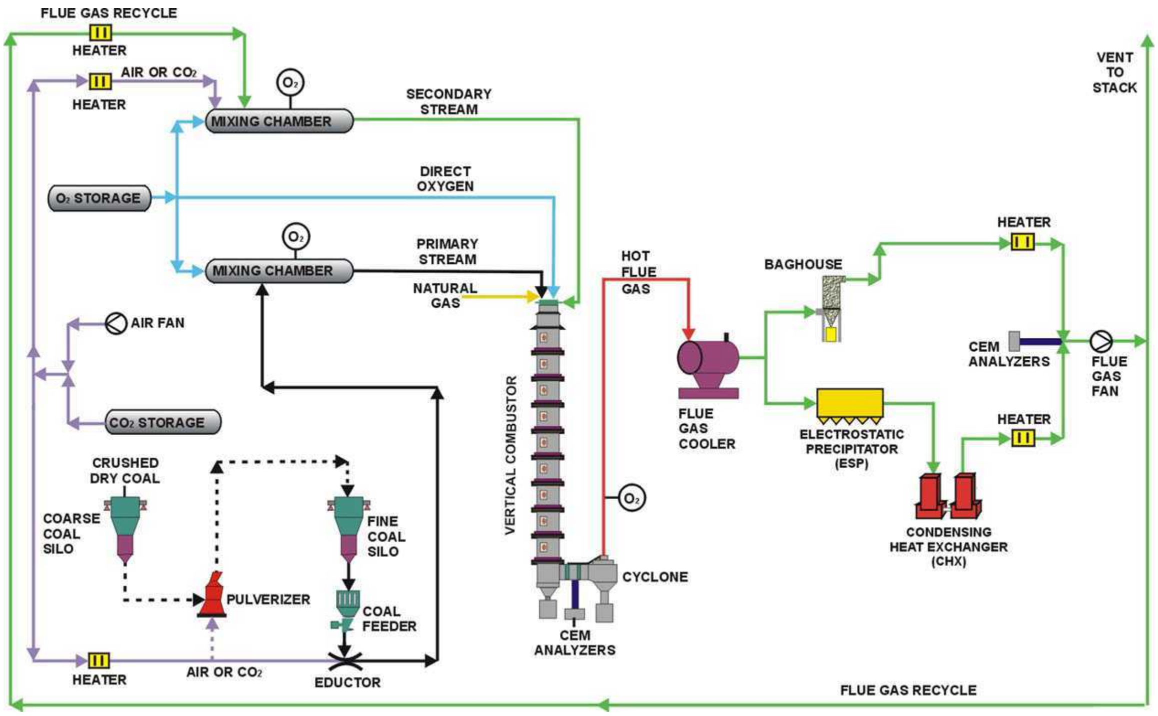

Figure 1- Current Configuration of the Vertical Combustor Research Facility

Figure 2 – Vertical Combustor Probing Access in Near Flame Region

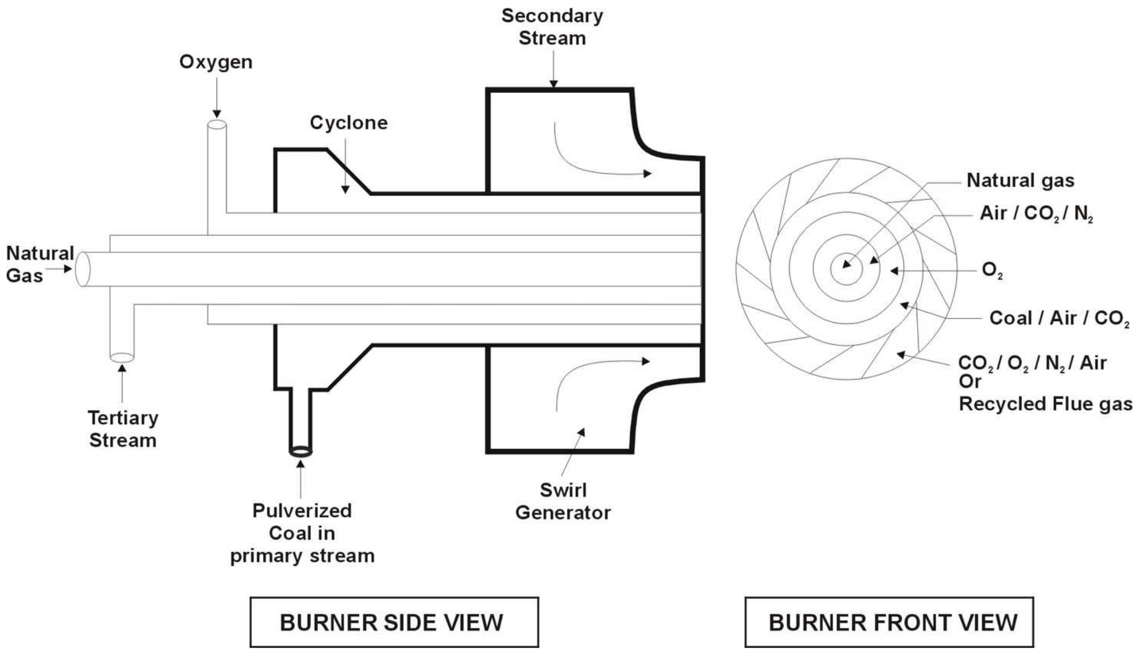

Figure 3 – Schematic of the Existing Burner

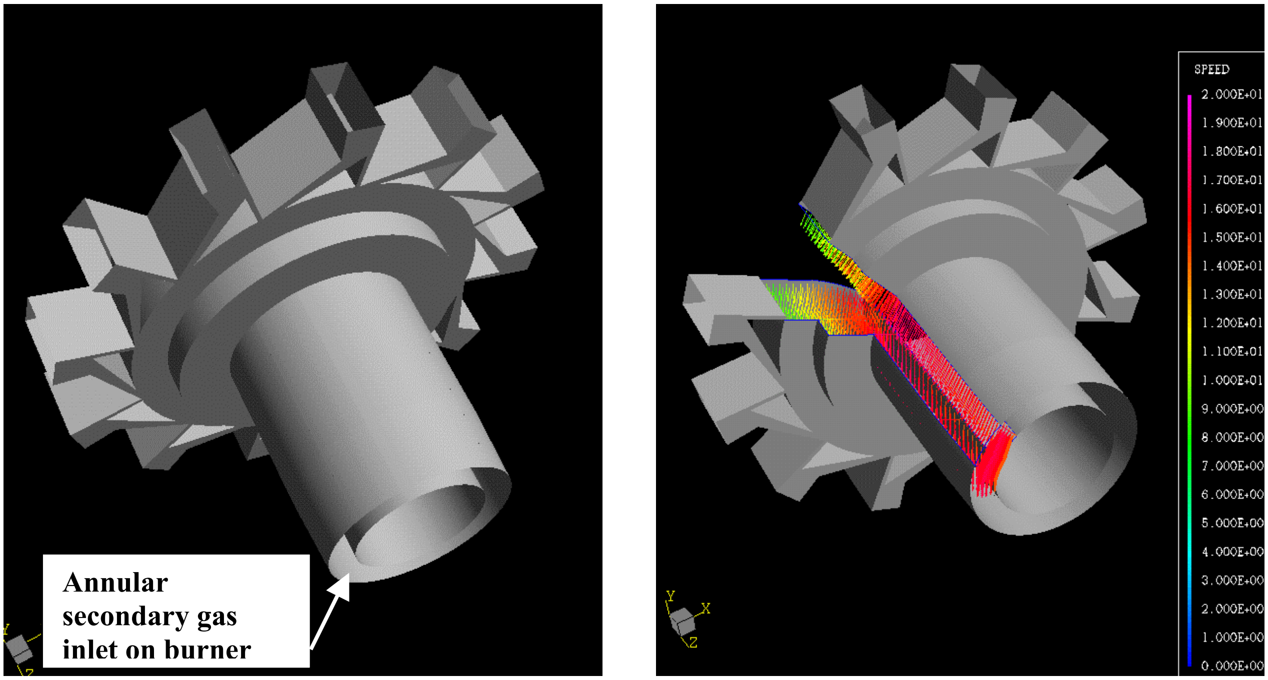

Figure 4: Swirl generator for the secondary gas upstream of burner face (with velocity vectors shown in the cut-out portion).

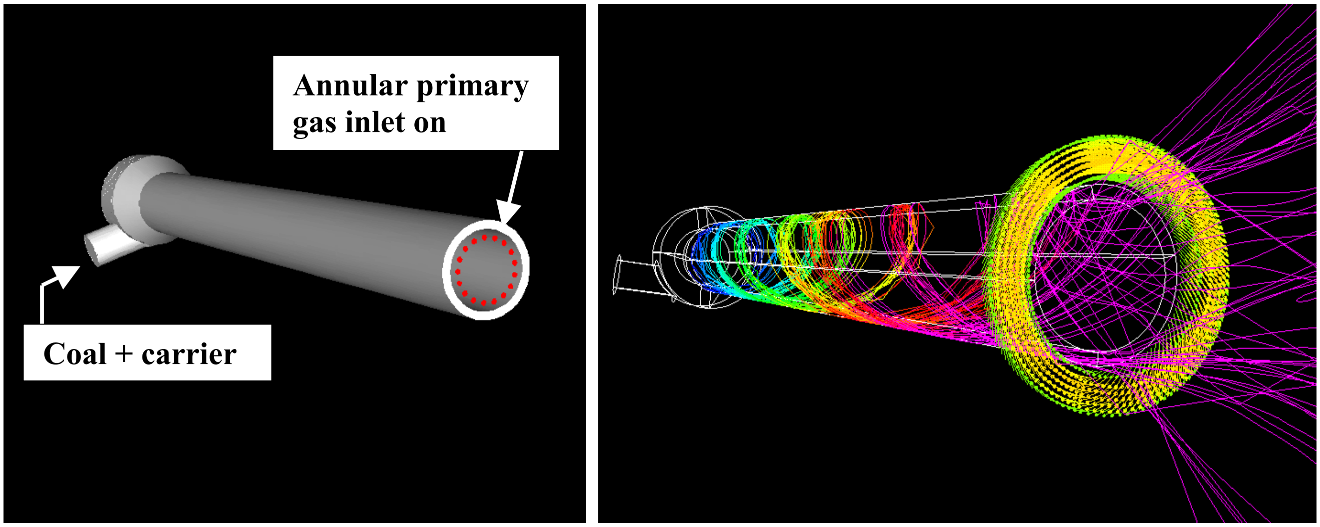

Figure 5: Coal delivery system shown with coal particle trajectories upstream of burner face.

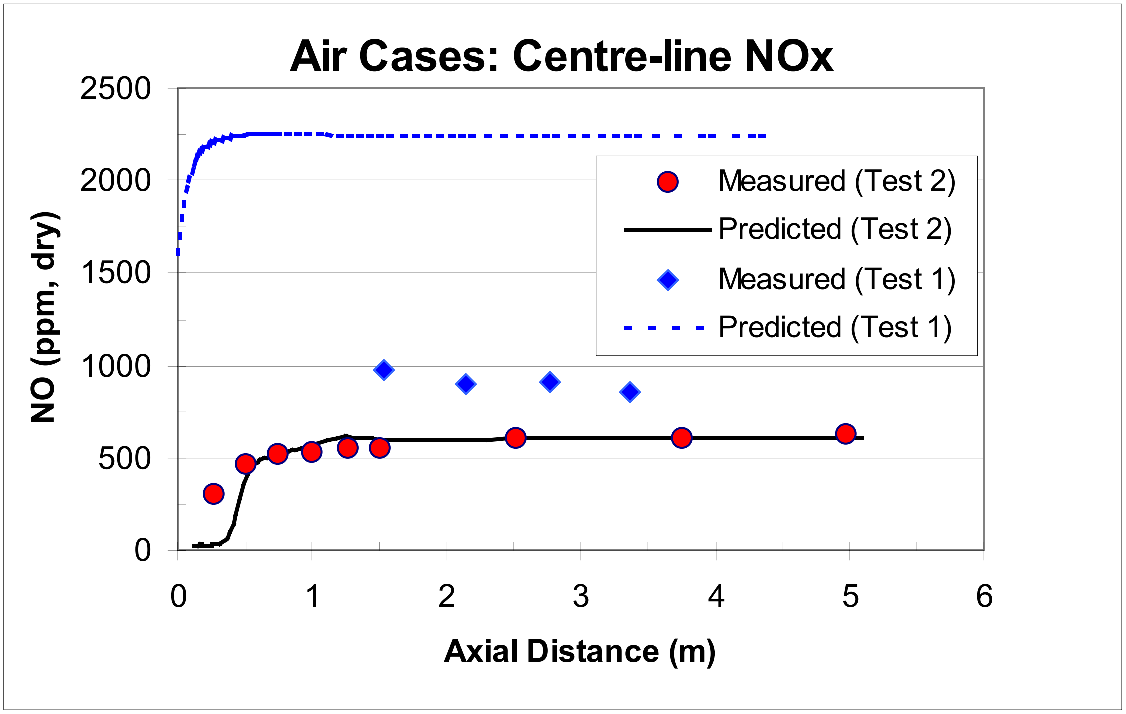

Figure 6: Comparison of predicted and measured NOx along furnace centre-line for two different coal combustion test cases performed in air. Dashed line: Test 1 2D axisymmetric simulation. Solid line: Test 2 full 3D simulation.

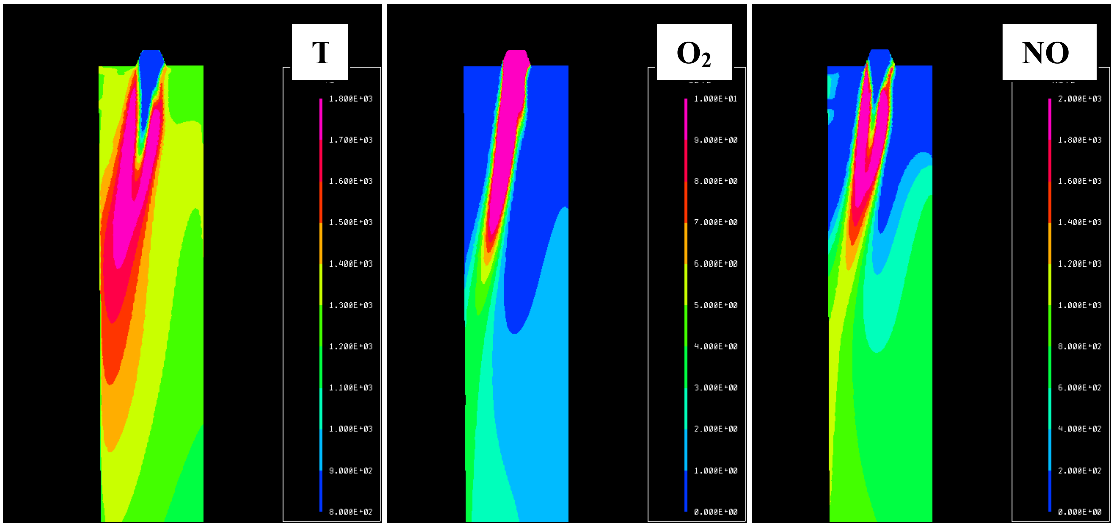

Figure 7: Temperature, O_2 and NO distributions across mid-section of furnace for dry recycle case.

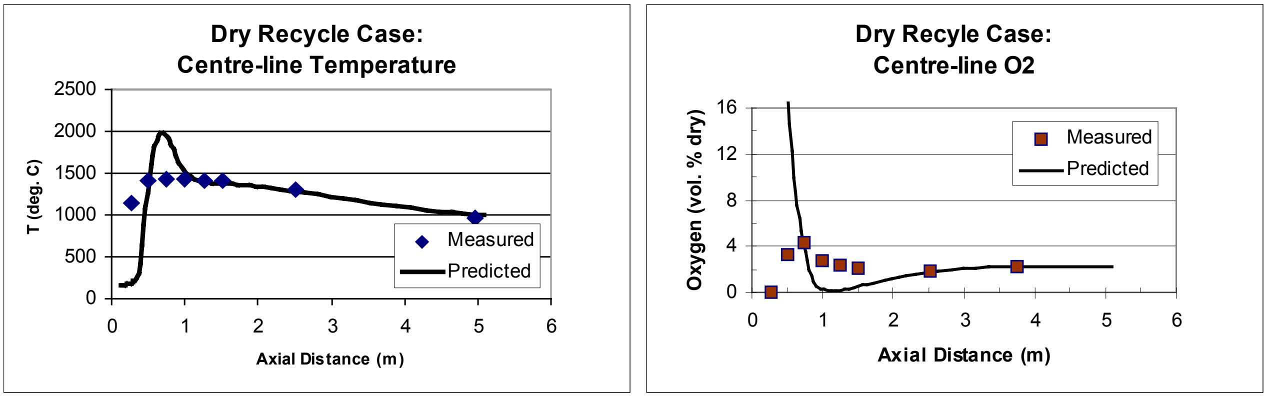

Figure 8: Comparison of measured and predicted temperature and oxygen along furnace centre-line for dry recycle case.