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# A Study of Combustion Characteristics of Pulverised Coal under MILD Combustion Conditions

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**Abstract**

In this experimental work, a laboratory-scale recuperative furnace has been used to investigate the sustainability of Moderate or Intense Low Oxygen Dilution (MILD) combustion with pulverised coal. Low-rank and high volatile Kingston brown coal and high-rank and low volatile Bowen Basin black coal with particle size in the range of 38-180 $\mu$m were injected into the furnace using either $CO_2$ or $N_2$ as a carrier gas. Operating conditions for stable MILD combustion of pulverised coal have been identified and evidencing MILD condition is achievable without any additional pre-heating of the air. The $O_2$ and CO emissions were measured in parallel with NO emission. A water cooled sampling probe was used to conduct in-furnace gas sampling. Measurements of in-furnace gas concentration of CO and NO and in-furnace temperatures are presented. It was found that a significant reduction of NO emission owing to the strong NO reburning reaction inside the furnace. These findings, together with the potentiality of MILD conditions for soot depression and destruction, open the possibility of using high rank black and low rank brown coal with this technology.

*Keywords: MILD combustion, pulverised coal, CO, NO.*

## 1. Introduction

Moderate or Intense Low Oxygen Dilution (MILD) combustion has been identified as an innovative approach for reducing the production of pollutants and increasing thermal efficiency from the combustion of fossil fuels. MILD combustion operates on the combination of heat and exhaust gas recirculation [1]. The recirculation of flue gas decreases the local oxygen concentration and increases the temperature of the reactants. The lower oxygen concentration slows the reactions and leads to a distributed reaction zone. As a result a distributed thermal field is established which leads to a semi-uniform temperature distribution with reduced peak temperature. Thus, thermal $NO_x$ formation is considerably reduced. MILD combustion is often called “flameless combustion” or “flameless oxidation” (FLOX®) [2] because at optimized conditions the flames are invisible and inaudible. This combustion is part of the “high temperature air combustion” (HiTAC) regime because the combustion air is usually preheated to high temperatures [3].

MILD combustion has been studied extensively for gaseous and liquid fuels and has been successfully used in many industrial applications [3]. It would be attractive if this technology could also be applied to coal combustion, as coal is one of the most abundant fossil fuels in the world and forecasts show that this position will remain unchanged over a foreseeable future [4]. Nevertheless, MILD combustion of pulverised coal has received much less attention than that of gaseous fuels and its burning characteristics are poorly understood. Some studies have recently been reported on pulverised coal combustion under MILD conditions [5-7]. An experimental study on the MILD combustion behaviour of high volatile coal was conducted in a semi-industrial scale furnace at 0.58MW thermal input by Weber et al. [7] at the International Flame Research Foundation (IFRF). High temperature air (1300 °C) was used to burn high volatile coal and the $NO_x$ emissions were in the range 160-175 ppm (at 3% $O_2$) indicating high $NO_x$ reduction potential of this technology for pulverised fuels. However, the basic mechanism of $NO_x$ formation is not clearly understood from the experiments.

There are substantial challenges to better understand the formation and destruction of pollutants, like $NO_x$ and $SO_x$ under MILD combustion of pulverised coal. The main focus of this research is to investigate the combustion characteristics of brown and black coal, as pulverised fuels, in a recuperative MILD combustion furnace. The effect of the carrier gas, fuel types and the operating parameters on the stability of the MILD combustion, in-furnace gas concentrations and temperature as well as the pollutants emissions in exhaust are discussed and analysed.

## 2. Experimental

### 2.1 Experimental Setup

In this study, a laboratory scale MILD combustion furnace (MCF) is used as shown in Fig. 1. This furnace was built and instrumented by Szegö *et al.* [8]. The furnace has a square cross section of 280 mm × 280 mm and a height of 585 mm and is lined with high-temperature ceramic fibre-board refractory. The furnace flow diagram is shown in Fig. 1. The furnace is preheated to temperatures above that of fuels’ autoignition, using a nonpremixed natural gas flame. The switch to MILD mode is achieved once the temperature at the lower corner of the furnace, which is

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identified as safety thermocouple (TC) on Fig. 1, exceeded 850 °C. The burner block and jet arrangement at the bottom of the furnace is shown in Fig. 2. The central fuel nozzle, with an internal diameter of 7.5 mm, is fitted with a bluff body (22 mm in diameter) and is surrounded by an air nozzle with an internal diameter of 26.4 mm.

When operated in MILD mode, the combustion air through the central air nozzle is switched to the four surrounding periphery jets, which have an internal diameter of 4 mm. Pulverised coal particles replace natural gas in the central fuel nozzle and is carried into the furnace using either $CO_2$ or $N_2$. The furnace is equipped with two cooling-loop heat exchangers on opposite sides to each other. Water is supplied to the heat exchangers at a constant inlet temperature and flow rate. These heat exchangers remove 4.5 kW, 4.83 kW, and 4.32 kW of heat on average for the combustion of $CO_2$ carried brown coal, $CO_2$ carried black coal, and $N_2$ carried brown coal, respectively.

The mole fractions of $O_2$, CO, and NO in the exhaust are measured using a TESTO Model 350XL portable gas analyser. The absolute errors of these measurements, according to the manufacturer's specifications, are $\pm 0.8\%$ (by volume) for $O_2$, $\pm 10$ ppmv for CO, and $\pm 5$ ppmv for NO of measured value.

The internal temperatures of the furnace are measured on the centreline ($x = 0\ mm$), across the height ($z$ axis) of the MCF for all experiments. Furnace temperatures are measured flush with the inner surface using a 6-mm-diameter sheathed Nicrosil-Nisil (N-type) thermocouple placed at 42.5 mm from the bottom of the furnace. Additional thermocouples with a 6 mm-diameter bead made of Pt/Pt 13%Rh (R-Type) are inserted horizontally at heights of 142.5, 242.5, 342.5, 442.5 and 542.5 mm. The exhaust gas temperature is measured at a distance of 100 mm from the furnace outlet with a stainless steel sheath type K (Ni–Cr) thermocouple. All temperature measurements are logged using a PC and USB-TC data logger.

A cyclone-based ash collector was used to separate ash particle from the exhaust gas stream using cyclonic separation method.

A sampling probe was developed for in-furnace sampling during MILD combustion. The probe consisted of three stainless steel concentric pipes, enabling cold water to circulate in the probe for rapid quenching of hot combustion gases.

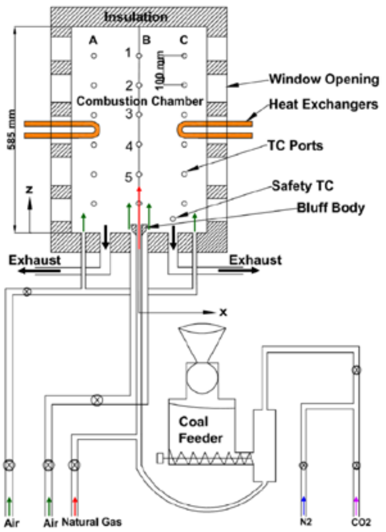
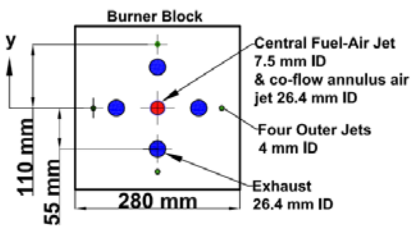



Fig. 1 Schematic diagram of the MILD combustion furnace and supply system




## 2.2 Characteristics of Coal

Two different types of coal were combusted in this experimental work. The Kingston brown coal which is a low-rank and high volatile lignite while Bowen Basin black coal which is a high-rank and low volatile anthracite. The coal particles were milled and sieved into 38 $\mu$m <d $\leq$ 180 $\mu$m size range. Proximate and ultimate analyses of the coals are presented in Table 1. The gross dry calorific value of brown coal and black coal is found at 20.0 MJ/kg and 31.9 MJ/kg respectively.

A coal feeder was specifically built for the purpose of decoupling the carrier gas flow rate from the solid particle supply rate. A small screw feeder that was operated using a stepper motor controlled the amount of coal, which was fed into the feeding chamber. The carrier gas was set at a constant flow rate.

## 3. Results and Discussion

Three different experiments were conducted using Kingston brown coal with either $CO_2$ or $N_2$ and Bowen basin black coal with $CO_2$ as the carrier gas. The coal particles carried by $CO_2$ or $N_2$ were supplied through the centreline jet, while the combustion air was supplied through the four periphery jets. A summary of the operating conditions is shown in Table 2.

Table 3: Analysis of coal (*wt% dry basis*)

| Ultimate Analysis | Kingston Brown coal | Bowen Basin Black coal |
|---|---|---|
| C | 52.5 | 81.2 |
| H | 3.6 | 3.6 |
| O* | 17.73 | 3.47 |
| N | 0.48 | 1.35 |
| S | 4.09 | 0.58 |
| Proximate Analysis | | |
| Fixed carbon | 35.7 | 80.7 |
| Volatile matter | 42.7 | 9.5 |
| Ash | 21.6 | 9.8 |

*balance

Table 2: Operating parameters and resulting emissions for MILD combustion using pulverised coal

| Parameter | $CO_2$ Carried Brown Coal | $CO_2$ Carried Black Coal | $N_2$ Carried Brown Coal |
|---|---|---|---|
| Thermal input (kW) | 14.5-15.2 | 14.7-15.8 | 14.5-15.9 |
| Equivalence ratio, $\phi$ | 0.86-0.90 | 0.85-0.91 | 0.86-0.92 |
| Central fuel jet velocity (m/s) | 7.92 | 7.92 | 10.43 |
| Periphery air jet velocity (m/s) | 86.2 | 86.2 | 86.2 |
| Measured CO in the exhaust (ppmv dry) | 2790-4996 | 331-547 | 1661-5179 |
| Measured NO in the exhaust (ppmv dry) | 178-228 | 296-366 | 164-236 |

## 3.1 Exhaust Emission

A time history of the mole fractions of $O_2$, CO, and NO in the exhaust for brown and black coal carried by $CO_2$ are shown in Fig. 3. The measured CO levels of brown coal were generally higher in these experiments than the black coal. For an equivalence ratio of $\phi = 0.89$ the CO levels were 4990 ppm but decreased at 2790 ppm at $\phi = 0.86$ in the case of brown coal. For black coal, CO level was almost constant at 450~500 ppmv. The higher CO emissions for brown coal is related to the more eminent char burnout of brown coal by the heterogeneous reactions between char ($C_{(s)}$) and gaseous products ($C_{(s)} + 1/2O_2 \rightarrow CO$, $C_{(s)} + CO_2 \rightarrow 2CO$, $C_{(s)} + H_2O \rightarrow CO + H_2$) of the combustion reaction. Consequently, the furnace temperature for this case was found lower due to the endothermic nature of the heterogeneous reactions. Minor variation in the feeding rate of the coal impacted on the equivalence ratio and the $O_2$ concentration in exhaust. The CO levels of black coal did not change significantly with the change in equivalence ratio owing to the incomplete char burnout (this issue is further discussed later in this paper) and low volatile content. This suggests that increasing concentration of CO is related to the effect of coal chemistry rather than $O_2$ levels.

The measured NO emissions from these flames are listed in Table 2. For brown coal the measured NO is ≤ 228 ppm while for black coal the value is ≤ 366 ppm. In particular, for an equivalence ratio of $\phi = 0.88$, the NO measurements were 178 ppm for brown coal and 320 ppm for black coal. It is speculated that higher flame temperature and higher nitrogen bounded in the fuel contribute to relatively higher NO emission for black coal.

## 3.2 Furnace Temperature

The measured mean temperature profiles for different conditions are shown in Fig. 4. The furnace temperatures are measured along the centreline and at 50 mm and 100 mm left from the centreline in the furnace for each case. It is clear that the temperature is quite uniform with as little as 100 K difference along the furnace. This semi-uniform temperature is a feature of MILD combustion and results from the strong recirculation of hot products and the reactants. In Fig. 4 (a) for brown coal carried by $CO_2$ case the furnace has lower temperatures than the other cases. This difference could be related to the slower heat release due to the high production of CO from the char burnout of brown coal carried by $CO_2$.

## 3.3 In-Furnace Sampling

Figure 5 shows the comparison of in-furnace NO mole fraction by volume between brown coal and black

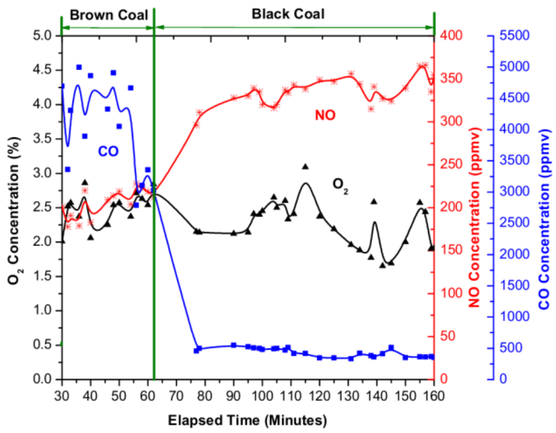
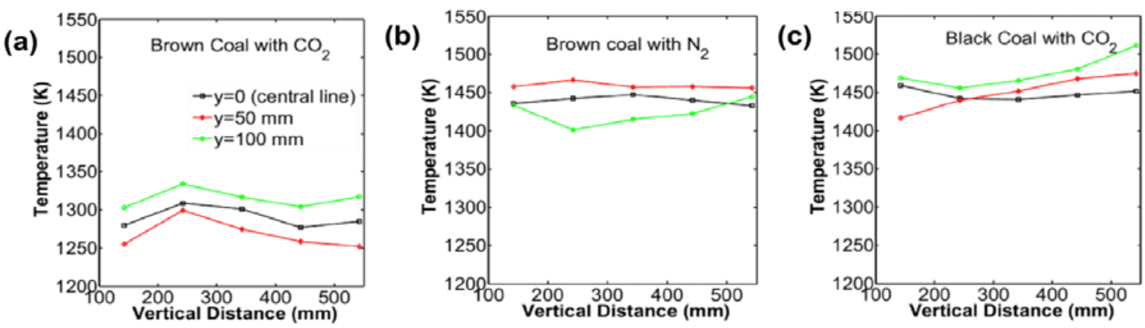



Fig. 3 Temporal variations of $O_2$, CO, and NO measured in the exhaust for $CO_2$ carried coal MILD combustion

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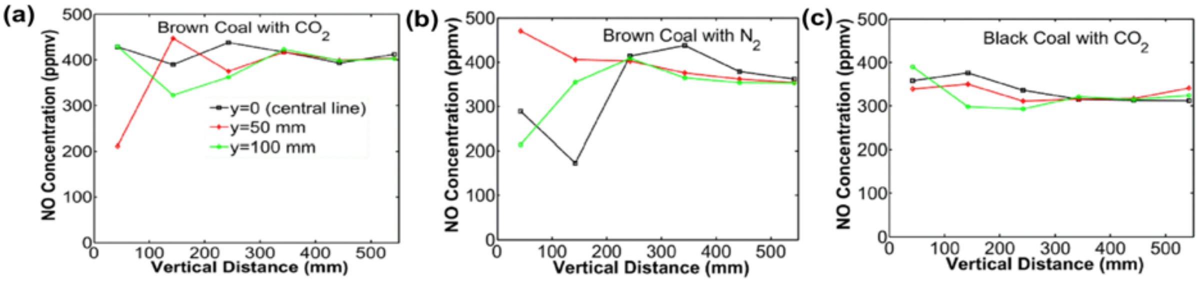

Fig. 5 In-furnace NO mole fraction at the centre (x= 0) along the horizontal distance (y-axis) of the furnace

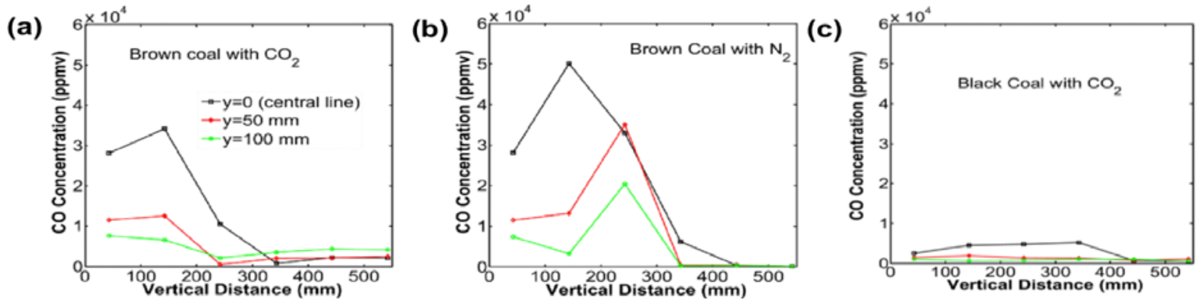

Fig. 6 In-furnace CO mole fraction at the centre (x= 0) along the horizontal distance (y-axis) of the furnace

n along the vertical direction (z axis) of the furnace. From the Fig. 5 (a) it is shown that when burning brown coal carried by $CO_2$, NO formation at the top portions of the furnace is consistent, ~400 ppm, while at the bottom (z = 42.5 mm) of the furnace NO mole fraction is decreased to 210 ppm near to the exhaust port (y = 50 mm). As the top part of the furnace is known to have recirculating products this result points to the reburning of NO. In case of black coal carried by $CO_2$, shown in the Fig. 5 (c), NO mole fraction in the furnace changes marginally and the level at the bottom of the furnace is around 350 ppm which is similar at exhaust for black coal combustion. For brown coal carried by $N_2$ the lowest NO mole fraction, ~173 ppm, was recorded at the centreline $(x = 0, y = 0)$ of 142.5 mm height of the furnace that may be attributed to the reburning mechanism which depends on the NO recombination with hydrocarbons.

Figure 6 shows a comparison of in-furnace CO mole fraction between brown coal and black coal combustion. For brown coal high mole fraction of CO, ~3.5-5%, was measured at the lower portion of the furnace due to the early volatile matter combustion. It is remarkable that at the middle parts of the furnace ($z =$342.5 $mm$), CO levels are found lowest, that suggests almost all of the fuels are being consumed here. On the other hand, for black coal in the Fig. 6 (c) CO mole fraction is found as not more than 0.5%. A large difference of CO production is mainly related to the char burnout phenomenon as large part of CO is produced from char burnout. By analysing the ash content of char from two different types of coal, it was found that only 38.9% carbon was consumed for black coal with $CO_2$, while for brown coal with $N_2$ and $CO_2$ as carrier gas show 91.7% and 83.04% carbon consumption in the furnace, respectively. Black coal produced small amount of CO because of the lowest char burnout. It is clear that residence time is not sufficient for the black coal case.

## 4. Conclusions

This paper reports on the successful burning of brown and black coal in a laboratory-scale furnace operating under MILD combustion. Results point to a major difference between the two coals and minor differences associated with the carrier gas. Results indicate that there is a strong NO reburning reaction inside the furnace and a relatively low emission in the exhaust. Ash content analysis of char showed that black coal was not burnt effectively, which is thought to be due to the relatively short furnace residence times. Further work is planned to better understand the devolatilisation region under MILD condition using advanced non-intrusive laser based techniques.

## 5. Acknowledgment

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