Effect of Coal Type and Oxyfuel Combustion Parameters on Pulverised Fuel Ignition

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Abstract

Oxyfuel combustion is currently one of the principal technological options being considered for capturing carbon dioxide from pulverised coal power plants. In oxyfuel combustion, coal is burnt in a mixture of recycled flue gases and added oxygen instead of in air. In principle this yields a flue gas containing only carbon dioxide, water vapour and small amounts other impurities. Oxyfuel combustion is superficially similar to combustion in air, but there are inevitable differences.

This paper describes ignition tests on pulverised coal suspensions using a suite of coals of different rank and from different countries of origin and over a range of oxygen and coal concentrations of interest for oxyfuel combustion. The ignition tests were carried out using the National Institute for Occupational Safety and Health (NIOSH) 20-litre explosion chamber. The purpose was to determine how easily the various coals ignite and burn in mixtures of O_2 and CO_2 compared to their combustion in air. The residual char volatile and ash contents for the ignition residues were measured using a thermogravimetric analyser (TGA), allowing Q factors (i.e., enhancement in apparent volatile yield due to higher heating rates and/or heterogeneous reactions) to be determined and compared.

An ignition index has been derived from the explosion and char data. This index has been used to rank low volatile coals for ignition propensity in air. The results show that to obtain ignition and combustion comparable to that in air, the oxyfuel O_2-CO_2 gas mixture must contain over 30% O_2.

Keywords
CO_2 capture, combustion, pyrolysis, oxyfuel.

INTRODUCTION

In oxyfuel combustion, coal is burnt in a mixture of recycled flue gases and added oxygen instead of in air, i.e., it is almost totally absent of nitrogen. In principle this yields a flue gas containing only carbon dioxide, water vapour and smaller amounts of NO_x, SO_x and other impurities, which could be sent directly to storage and subsequent sequestration in aquifers after the water vapour has been condensed.

Oxyfuel combustion is superficially similar to combustion in air, but there are inevitable differences. The higher specific heat capacity of carbon dioxide compared to that of air is an important factor. Because the CO_2 would absorb more heat, combustion of coals in an O_2-CO_2 mixture may lead to lower flame temperatures and hence lower ignitability compared with combustion in air at the same oxygen concentration (i.e. ~21% molar).

This paper reports the results of joint experimental research by Imperial College of London, England and NIOSH of Pittsburgh, USA on the ignitability of various coals dispersed in mixtures of oxygen and carbon dioxide.

EXPERIMENTAL

Coal ignition studies were carried out on six coal samples. The TGA microproximate analysis data are summarized in Table 1. Microproximate analysis is similar to standard proximate analysis but only requires ~10 mg of coal compared to ~1 g for standard analysis (Ottaway, 1982). The coals were selected based on rank, availability, and commercial importance. These included one US bituminous coal (from NIOSH) with volatile matter (VM) content of about 18 wt% dry basis and five low volatile coals (VM roughly between 6 and 13 wt% db) supplied by Doosan Babcock Energy Limited (formerly Mitsui Babcock Energy Ltd., MBEL). The ignition test program included the following parameters:
- effect of coal type,
- effect of coal dust concentration from 100 to 600 g/m^3 , and
- effect of gas atmosphere (air and gas mixtures from 21-40% O_2 v/v , balance CO_2).

TABLE 1 TGA microproximate analysis of the coal samples (in VM order).

Coal	Country of origin	Moisture (% ad)	VM (% db)	Ash (% db)	FC (% db)	VM (% daf)
NIOSH coal						
Pocahontas	USA	0.33	18.6	6.2	75.2	19.9
MBEL coals						
Qiyi	China	0.45	13.5	16.1	70.4	16.1
Chang Chun	China	0.44	13.1	15.4	71.5	15.5
Tower	UK	0.90	10.4	5.7	83.9	11.0
WFD	UK	0.43	8.5	6.7	84.8	9.1
Hongai	Vietnam	0.88	6.4	23.5	70.1	8.3

Note: ad =air dried, db=dry basis, daf=dry ash free

Ignition tests were carried out in the NIOSH 20-litre explosion chamber (Figure 1). Details of the apparatus have been described elsewhere (Cashdollar, 1996, 2000).

The NIOSH 20-litre ignition chamber is near-spherical in shape and made of stainless steel with a pressure rating of 21 bar (g). The top of the chamber is hinged and opens across the whole chamber diameter thus allowing easy access to the interior for sample loading and cleaning after each test (as shown in Figure 1). The hinged top is attached to the main body with six bolts. A strain gauge pressure transducer is used to measure the explosion pressure and rate of pressure rise. As this

transducer measures absolute pressures, it can also be used to monitor the evacuation of the chamber prior to the addition and dispersion of the test gas. Three sapphire windows serve as viewports. Pressure data were sampled at a rate of 2 kHz using a desktop computer. An in-house computer program allows the data to be processed, printed and stored.

The coal dusts, previously dried overnight in a desiccator, were ignited with Sobbe[TM] (Dortmund, Germany) chemical igniters. These generate a large number of hot particles but with little or no gas. The igniters were activated electrically with an internal fuse wire. Attempts were made to ignite each of the coal samples using a small 500 J igniter whenever possible. However, if it did not ignite, then a larger 1000 J igniter was used and, if necessary, a 2500 J igniter. After each successful ignition, the resultant char residues were recovered for analysis and weighed to establish mass loss during ignition. Weight loss or devolatilisation from the ignition process can be calculated in two ways. One is by 'ash tracer', which assumes the ash material from the coal to be inert (Equation 1).

Ash tracer weight loss: wt%db = 100 x (1 – coal ash / char ash)   [1]

However, this method is often unreliable – especially for coals with low ash contents where the error bars can be very wide. The ash also contains igniter residue material – such as barium oxide and zirconium oxide. Therefore, it was decided to use direct weighing to derive the weight loss values, i.e., simply weighing how much char is produced. This method must correct for the presence of igniter residues. In addition, since it is not possible to collect 100% of the material, a correction factor or collection efficiency has to be determined. This was established by carrying out 'blank' runs where coal samples were dispersed in the 20-litre chamber but not ignited at 100, 200, 400 and 600 g/m^3 loadings. A good correlation was obtained and a linear correction equation derived (Equation 2). The collection efficiency was typically about 85%. The amount of igniter residue was calculated by simple chemical stoichiometry given the fact that a 500 J igniter contains 120 mg of reactants. Larger igniters were scaled up pro rata.

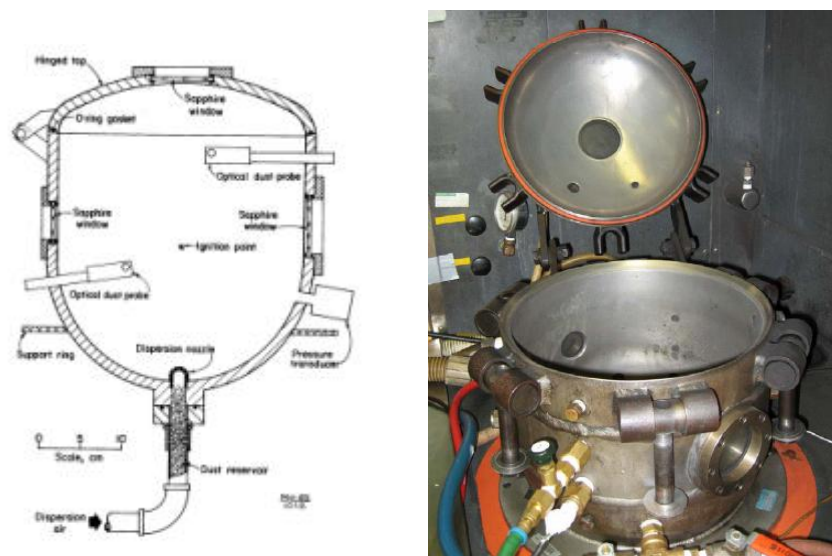Corrected char mass = mass char collected x 1.029 + 0.458 – igniter residue   [2]

FIGURE 1: Drawing and photograph of NIOSH 20-L explosion chamber.

From this, the weight loss from the ignition and combustion in the 20-L chamber can easily be calculated by Equation 3.

Weight loss, wt% ad = 100 x (1 – corrected char recovered / coal loaded)   [3]

Finally, this value can be converted to a dry-ash-free basis by Equation 4.

$$\text{Weight loss, wt\% daf} = \frac{100 \times \text{weight loss (wt\% ad)} - \%\text{moisture}}{100 - (\%\text{coal ash} + \%\text{moisture})} \qquad [4]$$

Char samples from the ignition tests were analysed in a Mettler-Toledo TGA/SDTA851e thermogravimetric analyser to give micro-proximate data (Ottaway, 1982). Samples (typically 10 mg) were heated in a 75 μL alumina crucible inside a TGA furnace with a flow of high purity nitrogen to 105°C then to 900°C (at 30°C/min), which gives respective values for moisture and volatile matter content. Finally, introduction of air resulted in 100% burn-off, allowing the fixed carbon and ash values also to be calculated. This procedure is similar to microproximate analysis of the original coal samples.

The Q-factor (Equation 5) represents the enhancement in volatile release under actual heating conditions compared to the release under proximate analysis heating (and volatiles transport) conditions.

$$\text{Q-factor} = \frac{\text{weight loss from volatile release (\%daf coal)}}{\text{Coal VM (\%daf)} - \text{Char VM (\%daf of original coal)}} \qquad [5]$$

This should not be confused with the R-factor (Equation 6), which is simply the quotient of the measured weight loss and the coal volatile matter (Kimber, 1967).

$$\text{R-factor} = \frac{\text{weight loss from devolatilisation (\%daf coal)}}{\text{Coal VM (\%daf)}} \qquad [6]$$

RESULTS

The results showed it was possible to ignite all the coals in air with the exception of one low volatile coal, Hongai. This coal could not be ignited even with the 2500 J igniter. This coal had the lowest volatile matter content (6.4%db) and highest ash content (23.5 wt% db) of all the coals tested and this probably had an effect on its ignition propensity. The higher rank (lower volatility) coals were significantly more difficult to ignite, as one might expect, but most ignited in air using the higher energy pyrotechnic chemical igniters (2500J) whereas the lower rank coals could be ignited with the smaller igniters even at low coal dust concentrations. Note that for simplicity reasons, successful ignitions using only the smallest igniters have been shown.

Data for two of the coals tested, Pocahontas and Tower, have been summarised in Figures 2 and 3, respectively. Peak pressure ratio (PR) is simply the ratio of the peak absolute pressure developed during combustion divided by initial (atmospheric) absolute pressure. A PR >2 was taken to indicate a positive ignition test (Cashdollar, 1996). Figures 2a and 3a show the peak explosion pressure ratios from the 20-litre chamber. The Q-factors (Figures 2b and 3b) were derived using Equation 5, and the corrected weight losses (Figures 2c and 3c) were calculated using Equation 4. Note that 21%O_2-CO_2 in the key refers to an O_2 and CO_2 gas mixture containing 21% O_2. Note also that the shape of the data points refers to the igniter energy used, with triangles for 500 J, diamonds for 1000 J, and squares for 2500 J.
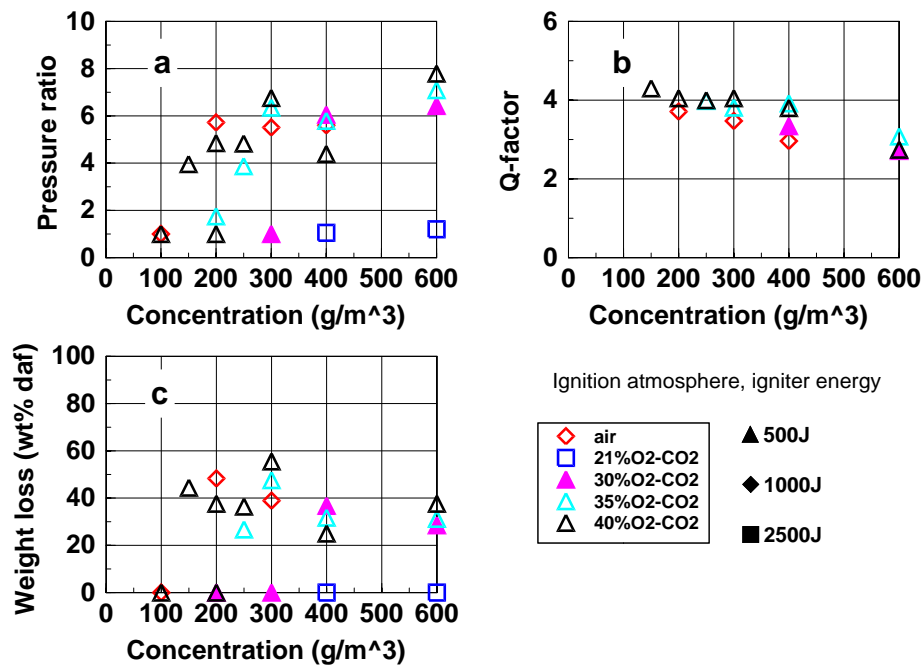

FIGURE 2: Effect of coal concentration and atmosphere type on Pocahontas coal ignition for a) pressure ratio, b) Q-factor and c) weight loss. (Q-factors shown only for those runs that achieved ignition, i.e. PR>2)
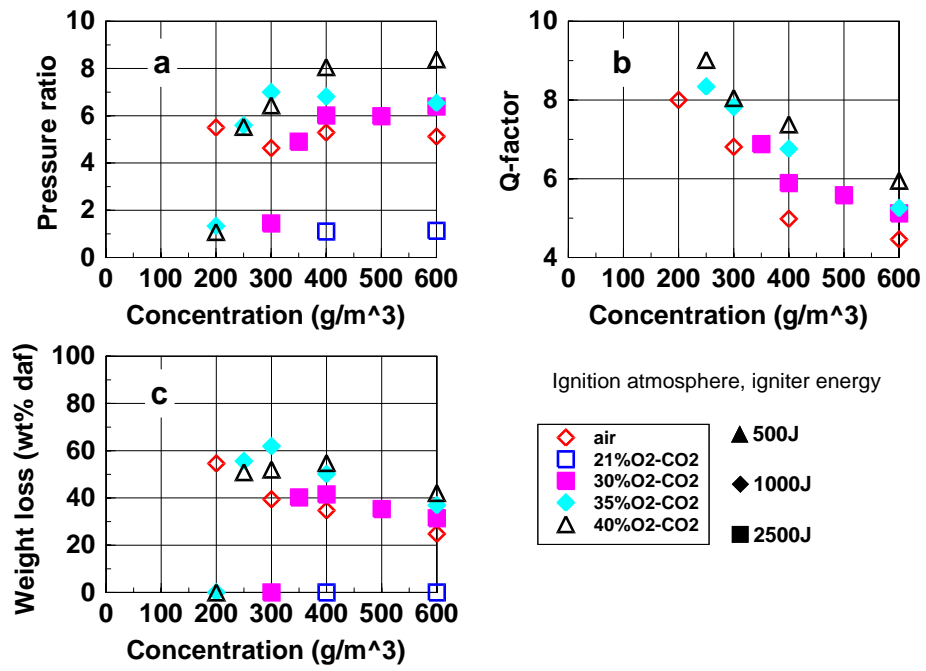
FIGURE 3: Effect of coal concentration and atmosphere type on Tower coal ignition for a) pressure ratio, b) Q-factor and c) weight loss. (Q-factors shown only for those runs that achieved ignition, i.e. PR>2)
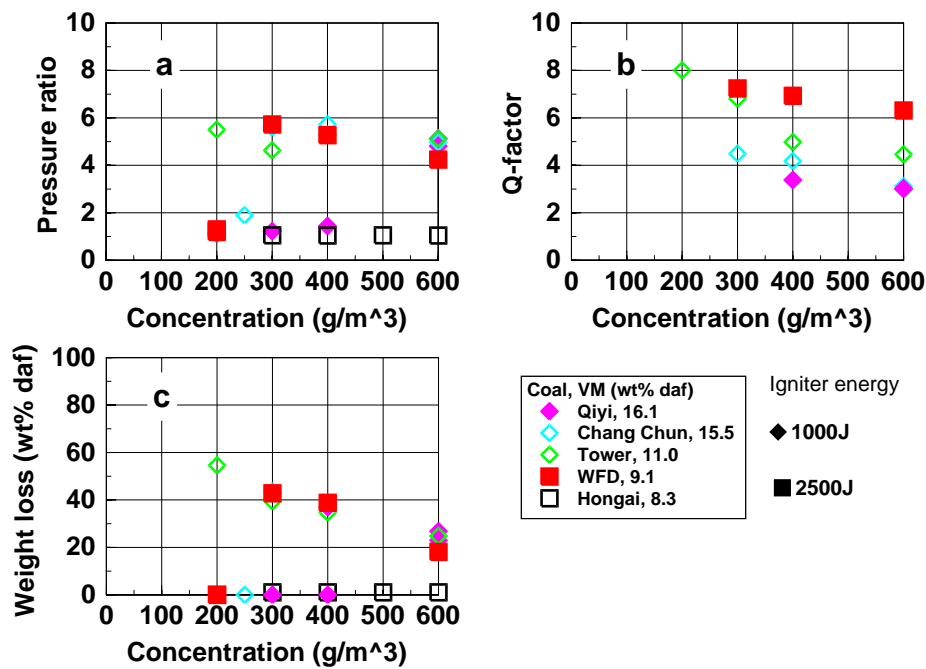
FIGURE 4: Comparison of coal ignition in air for 5 low volatile coals looking at the effect of coal concentration on a) pressure ratio, b) Q-factor and c) weight loss. (Q-factors shown only for those runs that achieved ignition, i.e. PR>2)

The ignitability of the various coals in air is shown in Figure 4. The Hongai coal has the lowest volatility and can not be ignited with the higher energy 2500 J igniter at any of the concentrations tested. The next higher volatile coal, WFD, can be ignited with 2500 J but not with 1000 J. The three highest volatile coals in Figure 4 could be ignited with the 1000 J igniter.

All of the coals were tested in the various O_2-CO_2 oxyfuel gas mixtures, producing data in a similar form as those in Figures 2 and 3. None of the coals listed in Table 1 ignited at 21% O_2 in the oxyfuel mixture. At an O_2 level of 30 or 35% in the oxyfuel mixture, the Pocahontas, Qiyi, Chang Chun, and Tower coals ignited with either the 1000 or 2500 J igniter. The WFD coal only ignited in the 30% O_2 oxyfuel mixture at 600 g/m^3 with a 2500 J igniter. It was possible to ignite the WFD coal in 35 and 40% O_2 oxyfuel gas mixtures using the 1000 J igniters at 300-600 g/m^3. The Hongai coal could not be ignited even with the 2500 J igniters at 40% O_2 in the oxyfuel mixture.

To reduce the subjectivity in assessing the coals in terms of ignition, a numerical 'ease of ignition' index (Equation 7) is proposed in order to rank the low volatile coals (which are known to be difficult to ignite) for their ability to ignite in air. In Equation 7, the "maximum weight loss" is maximum of the weight loss calculated from Equation 4 over the range of dust concentrations tested. The "maximum pressure ratio" is the highest explosion pressure ratio in air over the range of concentrations tested.

$$\text{Ignition index } = \text{ max. weight loss (wt\% daf) } \times \text{ max. pressure ratio} \qquad [7]$$

The ordering of the coals using this index for the two igniter energies is shown in Table 2, with highest ignition index at the top. Some of the variations, such as the difference between the 1000

and 2500 J data for the Tower coal, were due to the limited number of tests. The ease of ignition index order roughly correlates with coal rank order, but with one or two important exceptions. From the mean values, Qiyi and WFD coals appear to be comparable in ignitability (in air) from this evaluation method despite having quite different volatile matter contents. This trend matches some industrial experience of firing low volatile coals in wall-fired burners (Cameron, 2005).

TABLE 2 Coal ranking by ignition index

Coal ignitability	TGA Proximate VM %daf	Ignition index for two igniter energies		
		1000J	2500J	Mean
Chang Chun	15.5	243	306	274
Tower	11.0	300	243	271
Qiyi	16.1	211	232	221
WFD	9.1	176	245	210
Hongai	8.3	0	0	0

CONCLUSIONS

A number of low volatile coals have been tested and ranked for ease of ignition in air and in an oxyfuel mixture of O_2 in CO_2 at various concentrations ranging from 21 to 40% O_2. The ignition order in air generally followed coal rank but an alternative index is suggested based on the product of maximum weight loss and explosion pressure. This appears to correspond better with observed ignition behaviour in actual burner trials. There were relatively small differences between the various coals at the 40% O_2 level. The low volatile coals showed higher than expected weight losses probably due to some heterogeneous combustion occurring in the test chamber. Therefore the weight loss values shown are not exclusively from devolatilisation processes.

Apart from Hongai, which did not ignite, all the coals ignited in O_2 in CO_2 at some point. The concentration of O_2 in CO_2, which gave ignition comparable to that in air, was established to be between 30 to 35% v/v. This is consistent with data reported by Tan (2006), who concluded that the heat flux from oxyfuel experiments between 28 and 35% v/v O_2 in CO_2 was comparable to that carried out in air. Few coals ignited in 21% v/v O_2 in CO_2 even with the large 2500J igniter.

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