Evaluation of carbon black slurries as clean burning fuels

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Experiments were performed to examine the pumpability, atomization and combustion characteristics of slurries made of mixtures of carbon black with No. 2 fuel oil and methanol. Carbon black No. 2 fuel oil and carbon black methanol slurries, with carbon black contents of up to 50 and 45 wt%, respectively, were pumped and atomized by means of a peristaltic pump and air atomizing scheme, and burned in an 82 kW laboratory combustor. Measurements of slurry spray droplet size distributions indicated mean droplet diameters of approximately 100 and 30 μm for the carbon black–No. 2 fuel oil and carbon black methanol mixtures, respectively. Particulate emissions from the combustion of slurries containing 47 wt% carbon black in No. 2 fuel oil and 42 wt% carbon black in methanol were approximately 40 and 28 mg dm^{-3}, respectively. These particulate emissions are significantly higher than corresponding emissions from 'base case' No. 2 fuel oil and methanol tests (0.75 and 0 mg dm^{-3}, respectively). However, in spite of the increased particulate emissions, carbon monoxide emissions from all tests were similar (less than 50 ppm dry, corrected to 0% oxygen, for furnace stoichiometric ratios of 1.05 or greater). In addition, at 20% excess air, nitric oxide emissions from the combustion of the carbon black No. 2 fuel oil and carbon black methanol (approximately 50 and 15 ppm, respectively) were approximately half of those measured from the combustion of No. 2 fuel oil and methanol (105 and 30 ppm, respectively). Although not examined here, the use of dispersants, stabilizers and modifications to the atomization equipment could improve the burning characteristics of carbon black slurries.

(Keywords: carbon black; combustion; evaluation)

The Hydrocarb process[1-4] is being evaluated by the US Department of Energy (DOE) and US Environmental Protection Agency (EPA) as a two-step method for converting carbonaceous raw materials to particulate carbon and hydrogen-rich fuel gas or synthesis gas. In the first step of the process, carbonaceous raw materials, such as coal, biomass, or municipal wastes, are hydropyrolysed to yield methane-rich process gas with smaller equilibrium concentrations of carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), hydrogen sulfide (H_2S), nitrogen (N_2) and solid ash residue. In the second step, methane is thermally cracked to produce fine particulate carbon (carbon black) and hydrogen gas. A portion of the hydrogen-rich gas is recycled to the hydropyrolyser, while the remaining is withdrawn as a clean medium heating value fuel gas or converted to methanol.

The carbon black product from the thermal cracking step has an average particle size of between 1 and 2 μm diameter and is essentially free of ash, sulfur, oxygen and other impurities. Since carbon black has significant heating value (32.78×10^6 J kg^{-1}), it can be burned as a powder, in a manner similar to burning pulverized coal, or it can be slurried for use in liquid fuel combustors. Alternatively, portions of the carbon black can be sequestered to reduce the atmospheric CO_2 burden. In contrast to energy intensive coal gasification or liquefaction processes, Hydrocarb's hydropyrolysis (endothermic) and thermal cracking (exothermic) steps result in a relatively overall energy neutral process.

In a preliminary assessment of carbon black for use as a fuel, Koppel *et al.*[5] describe results of differential thermogravimetric analyser (DTGA) tests. Their results show that carbon black's lack of a volatile component requires higher ignition temperatures (approximately 660 C) for stable combustion, compared to those typically required for a pulverized high volatile bituminous coal (approximately 400°C). However, this study also concluded that, because of its small particle size, carbon black's burning rate was higher than that of a high volatile bituminous coal.

Preparation procedures and physical, thermal and rheological properties of slurries of carbon black with water, methanol and oil have been documented by Wei and Steinberg[6]. In addition, general combustion properties of slurries made of mixtures of carbon black and JP-10 (aviation fuel) have been examined in bench scale gas turbine combustors[7,8] and well stirred reactors[9]. These studies have shown that, to attain good combustion efficiencies, carbon black slurries require greater residence times than those needed by conventional liquid fuels.

Mechanisms of carbon black slurry combustion have been examined to gain a better understanding of these residence time requirements. Szekely and Faeth[10,11] have

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shown that, for slurries made of mixtures of carbon black and JP-10, combustion of individual slurry droplets (400–1000 μm diameter) in a turbulent diffusion flame is a two stage process, similar to combustion of coal slurries. In the first stage, the slurry liquid evaporates leaving a porous agglomerate of carbon black particles. In the second stage, the carbon black agglomerate burns in a similar manner as a coal char particle. Measurements showed that heat-up and combustion times for these agglomerates required 90–95% of the slurry droplet's lifetime. As with coal char combustion, post-flame quenching of the carbon black agglomerate yields poor carbon burnout. Motivated by these findings, flat flame burner studies of agglomerate combustion have been conducted[10 12]. In the first of these studies, agglomerate temperature, diameter, mass and velocity were measured as a function of residence time for initial agglomerate sizes representative of practical combustion conditions (10–75 μm diameter). These measurements were compared with a variable density, shrinking-sphere agglomerate reaction model and were shown to correlate satisfactorily. The study concluded that the density of the agglomerates and the empirical parameters used in the model varied with the extent of carbon reaction, but these variables were relatively independent of the initial agglomerate diameter and flame conditions. The second study extended these investigations to include blends of carbon black particles of different sizes. The combustion of blends containing 50 wt% each of 70 and 300 nm particles was found to take 10 50% longer than monodisperse particles at similar combustion conditions. However, it was concluded that improved atomization through proper blending would produce smaller droplet sizes, and smaller agglomerates would reduce residence time requirements.

To provide a preliminary assessment of the issues associated with the use of carbon black slurries as fuels for boilers and industrial furnaces, the US EPA Air and Energy Engineering Laboratory (AEERL) conducted a series of pilot scale tests based on carbon black slurry samples provided by the US DOE Brookhaven National Laboratory (BNL). In these tests, pumpability, atomization and combustion characteristics of these slurries were examined using an 82 kW horizontal tunnel combustor. These results are intended to complement previous smaller scale research efforts examining properties and combustion characteristics of carbon black slurries, and provide data for future larger scale combustor-fuel development efforts. Specific objectives include evaluation of pumping and atomization potentials for several carbon black formulations with No. 2 fuel oil, methanol and water; examination of maximum pumpable slurry concentrations; assessment of flame ignition and stability; and quantification of gaseous and particulate pollutant emissions as functions of excess oxygen.

EXPERIMENTAL

Combustion apparatus

Experiments were performed using the small semi-industrial scale 82 kW horizontal tunnel combustor illustrated in *Figure 1*. This 396.2 cm long, modular, steel-shell, refractory-lined research combustor was designed for the evaluation and characterization of fuels and combustible wastes. The 50.8 cm inside diameter (i.d.) burner section allows near-burner zone aerodynamic simulation of natural gas and fuel oil flames. Quartz observation windows permit visualization of flame shapes, spray patterns and burner operation. Following the burner section, the 25.4 cm i.d. back sections are equipped with numerous access ports permitting temperature measurements, time (position) resolved gaseous and aerosol sampling, and injection of various agents. However, for the research results presented here, gaseous and particulate samples were taken only from the stack locations indicated in *Figure 1*. These sampling locations are downstream of a water-cooled heat exchanger designed to protect the 20.3 cm i.d. stainless steel exhaust stack from excessive heat. From the experimental unit, exhaust gases are routed to a central facility air pollution control system (APCS) consisting of an afterburner, water quench, baghouse and acid gas scrubber. The APCS is designed to control air emissions and meet the requirements of the facility's resource conservation and recovery act (RCRA), research, development and demonstration (RD&D) and air pollution permits.

Fuels and combustion air are introduced into the burner section through an International Flame Research Foundation (IFRF) type moveable block variable air swirl burner. Air swirl is controlled by adjustment of the internal block spacing, permitting various turbulent diffusion flame types (shapes) to be generated, ranging from long axial (IFRF type 0) low swirl flames to short bushy (IFRF type 2) high swirl flames. Fuel is introduced through an interchangeable injector, positioned along the centre axis of the burner. Swirling air, passing through the annulus around the fuel injector, promotes flame stability and attachment on the water-cooled quarl. For the research results presented here, however, only one flame type was examined. This high swirl (IFRF type 2) flame with internal recirculation was produced with a burner block setting of 7 (on a 0–8 scale), resulting in a swirl number of approximately 1.48, as defined by Beer and Chigier[13].

To accommodate the atomization of viscous slurries, a special twin fluid (air atomizing) injector was constructed. As shown in *Figure 2*, this injector incorporates a central fuel–slurry tube and annular atomizing air. A convergent tip promotes fuel slurry atomization. Flow rates of the fuel–slurry and atomizing air streams are controlled

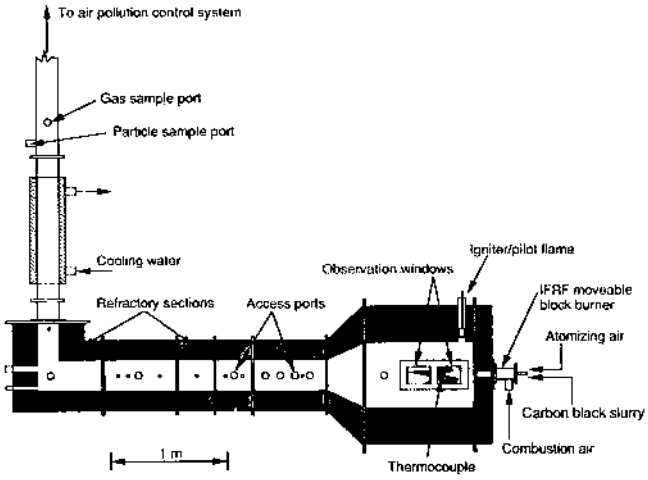

Figure 1 EPA horizontal tunnel combustor

independently. As mentioned above, the development of a slurry pumping and atomization system was an objective of this research, and is further discussed below.

Gas samples extracted from the stack location identified in *Figure 1* were continuously analysed to determine concentrations of the combustion gases; oxygen (O_2), CO, CO_2 and nitrogen oxide (NO). These routine continuous emission monitor (CEM) measurements were made to verify combustion conditions, maintain steady-state requirements, monitor pollutant species and serve as independent checks of air and fuel flows. In addition to CEMs, selected combustion tests quantified particulate emissions by the EPA modified method 5[14]. Several unshielded thermocouples are located along the length of the furnace to monitor centreline gas temperatures. One such thermocouple is located in the burner section, 22.9 cm from the burner quarl. Temperatures monitored at this location determine the characteristic combustion temperature reported in later sections.

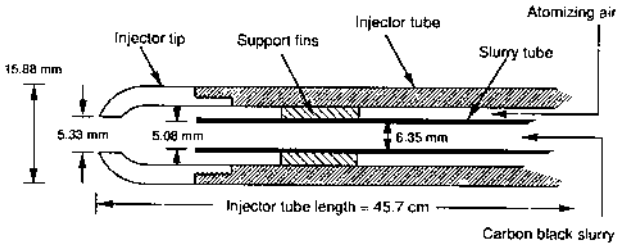

Figure 2 Fuel–slurry air atomizing injector

Carbon black slurries

Table 1 describes the five carbon black slurry samples received from Brookhaven National Laboratory, and included for testing. In these samples, carbon black is mixed with No. 2 fuel oil or methanol to act as a fuel extender or mixed with water to produce a 'pumpable liquid' fuel for potential boiler and industrial furnace applications. These slurries are identified in *Table 1* as samples 1–5. To provide baseline comparisons, experiments with unadulterated 'base case' No. 2 fuel oil (sample A) and methanol (sample B) were also planned. In addition, tests were included to examine slurry mixtures with higher concentrations of carbon black (within pumping and atomizing limits). These additional samples are identified as A1 and A2, and as B1, B2 and B3 to represent additional carbon black–No. 2 fuel oil and carbon black methanol mixtures, respectively. No additional carbon black water slurries were examined. *Table 2* summarizes the 12 carbon black mixtures considered.

Development of a slurry pumping and atomization system. To augment the 11 slurry samples received from Brookhaven National Laboratory, a commercial carbon

Table 1 Carbon black slurry samples received from Brookhaven National Laboratory

Sample	Composition (wt%)	Heating value (10^6 J kg^{-1})	Viscosity (cP)	Density (g cm^{-3})
1	44% CB[a]:55% water:1% No. 2 fuel oil	14.65	75	1.30
2	42% CB:58% methanol	26.17	51	1.06
3	51% CB:49% water	16.70	118	1.34
4	47% CB:53% No. 2 fuel oil	37.98	140	1.18
5	60% CB:40% water	19.70	752	1.43

[a]Carbon black

Table 2 Pumping and atomizing results for various fuel and carbon black slurries[a]

Sample	Composition (wt%)	Slurry flow rate (g min^{-1})	Atomizing air pressure (kPa)	Atomizing air flow rate (m^3 h^{-1})	Remark
A	100% No. 2 fuel oil	81.19	192.32	1.68	
4	47% CB[b]:53% No. 2 fuel oil	92.69	205.42	1.72	
A1	50% CB:50% No. 2 fuel oil	93.68	210.24	1.73	
A2	55% CB:45% No. 2 fuel oil				Unable to pump/atomize
B	100% methanol	156.02	188.88	1.68	
2	42% CB:58% methanol	134.54	206.11	1.72	
B1	45% CB:55% methanol	133.63	217.82	1.80	
B2	50% CB:50% methanol	131.51	–	–	Unstable flow
B3	60% CB:40% methanol	–	–	–	Unable to pump/atomize
1	44% CB:55% water:1% No. 2 fuel oil	–	–	–	Unable to pump/atomize
3	51% CB:49% water	–	–	–	Unable to pump/atomize
5	60% CB:40% water	–	–	–	Unpumpable

[a]Samples A and B represent unadulterated 'base case' fuels. Samples 1, 2, 3, 4 and 5 correspond to Hydrocarb samples received from Brookhaven National Laboratory. Samples A1, A2, B1, B2 and B3 represent other carbon black/fuel compositions. Based on pumping and atomizing results, samples A, 4, A1, B, 2 and B1 were determined suitable for further experimentation as combustion fuels. Samples A1 and B1 represent maximum carbon black concentrations that could be successfully atomized
[b]Carbon black

black was purchased and additional quantities of slurries were formulated per the information given in *Table 1*. Of the five slurries received for evaluation, sample 4, the carbon black–No. 2 fuel oil formulation (see *Table 1*) seemed most promising in terms of its heating value and potential ignitability (high volatile content). In addition, based on its relatively high viscosity (see *Table 1*), sample 4 would also likely be more difficult to pump and atomize than samples 1, 2 or 3 (sample 5 presented unique problems). Based on these considerations, the development of a pumping and atomizing scheme was initiated using sample 4. As expected, sample 4 appeared fairly viscous (similar to thick pancake batter) and did not flow freely. In addition, it was believed that the presence of the carbon black particles in suspension made this slurry abrasive to pumping equipment analogous to similar behaviour seen for coal water slurries[15]. Several types of pumps were evaluated, including diaphragm, screw and gear types. None of these pumping systems were successful in pumping this slurry. In all such trials, persistent clogging of pump flow passages and/or erosion of pump seals occurred. Finally, a peristaltic pump was tried and found to provide reliable, adjustable and accurate flows and pressures through nominal 0.64 cm flexible Tygon tubing. In this type of pumping arrangement, component erosion is eliminated by preventing contact between slurry and pump parts. Peristaltic pumps have been used previously to pump coal–water slurries in small scale applications[16].

Efforts were made to obtain pressure atomization nozzles suitable for slurry applications. Unfortunately, none of the manufacturers contacted offered such nozzles within the design flow rates and existing burner dimensions. In addition, none of the available hollow cone or centrifugal pressure nozzles typically used for distillate fuel oil atomization were suitable for use with the slurry. Experiments with these designs quickly ended with high pressure drops and nozzle clogging. Twin-fluid atomizers, however, have been used previously to atomize coal water slurries[17], and a technique based on the modified designs described by Marshall[18] was employed here. This design uses compressed air to disintegrate a stream of viscous fluid. The fabricated twin-fluid atomizer is illustrated in *Figure 2*. Together, the peristaltic pump and twin-fluid atomizer were used to produce a fine spray for a slurry flow rate of approximately 5.6 kg h^{-1} (required to yield a 58.6 kW firing rate for sample 4). The atomizing air flow and pressure required for this atomization arrangement were approximately 28.6 l min^{-1} and 205.52 kPa, respectively.

It should be noted that the pumping and atomizing system developed here describes just one successful method of delivering these slurries for these laboratory scale tests. It is likely that other pumping and atomizing arrangements are possible, especially at larger scale. However, the dimensions of the small IFRF type burner used here severely limited the tubing sizes and nozzle diameters that could be used. These small spaces prevented the use of pressure atomizing devices and likely promoted plugging, high pressure drops and premature pump wear. In fact, it is unlikely that a peristaltic pump arrangement would be suitable or practical for larger scale applications.

Table 2 identifies 12 samples for which pumping and atomizing tests were conducted using the peristaltic pump and twin-fluid atomizer described above. As mentioned previously, these samples include the five samples received from Brookhaven National Laboratory, 'base case' No. 2 fuel oil and methanol samples, and five additional carbon black–fuel formulations included to examine pumpability limits. As seen in *Table 2*, the three carbon black–water and carbon black–water–No. 2 fuel oil slurries (samples 1, 3 and 5) were not pumpable. These slurries were too viscous to flow within the pumping arrangement. Likewise, efforts to pump samples A2 and B3 (samples containing highest carbon black concentrations) produced similar results. Sample B2, a 50:50 mixture of carbon black and methanol would flow; however, its atomization resulted in unstable uncontrollable flow rates. The six remaining samples (A, 4, A1, B, 2, B1) were each pumpable and could be atomized to produce suitable sprays for further combustion testing. *Table 2* summarizes atomizing air pressures, flow rates and slurry flow rates for these six samples to yield a nominal 58.6 kW combustor load. Samples A1 and B1 represent the maximum carbon black concentrations in No. 2 fuel oil and methanol, respectively, that could be pumped and atomized with the chosen pumping and atomizing arrangement. No further efforts were made to examine carbon black–water mixtures. It should be noted that this study did not examine the effects of numerous dispersants or stabilizers that might be added to improve the fuel handling properties. It is likely that the proper selection of these additives may have permitted the pumping of the carbon black–water mixtures and improved the characteristics of the No. 2 fuel oil and methanol samples. However, a parametric examination of dispersants and stabilizers was deemed to be outside the scope of this research.

While the particle size distribution (PSD) of the atomized slurry is a function of many factors, including slurry viscosity, surface tension, density, fluid velocities and flow rates, and measurement location, *Figure 3* presents typical droplet PDSs produced by the pneumatic atomizer shown in *Figure 2* for the six pumpable samples. These droplet PSDs were measured with a Fraunhofer diffraction particle sizing technique[19,20], using the slurry and atomizing air flow rates presented in *Table 2*. The sampling location was 10.16 cm from the nozzle tip. *Figure 3* shows that both the No. 2 fuel oil and methanol (solid symbols) produce distributions with similar mean particle size (approximately 40 μm diameter). The methanol, however, produces a slightly narrower distribution. In comparison to the 'base case' PSDs, the PSDs for the slurries (open symbols) are most interesting. Both carbon black No. 2 fuel oil mixtures produce PSDs with larger mean diameter (approximately 100 μm) compared to the base case No. 2 fuel oil. Conversely, both carbon black–methanol mixtures produce PSDs with mean diameters (approximately 30 μm) slightly smaller than the base case methanol. This behaviour is likely due to differences in viscosity, surface tension and density between the samples[18]. The PSDs produced, however, indicative effective atomization and the production of fine sprays for the six pumpable slurries.

Combustion emissions

Before each combustion test, the combustor was fired (preheated) overnight using natural gas (58.6 kW). Prior to the introduction of a slurry, the natural gas flame was turned off, and the gas injector replaced

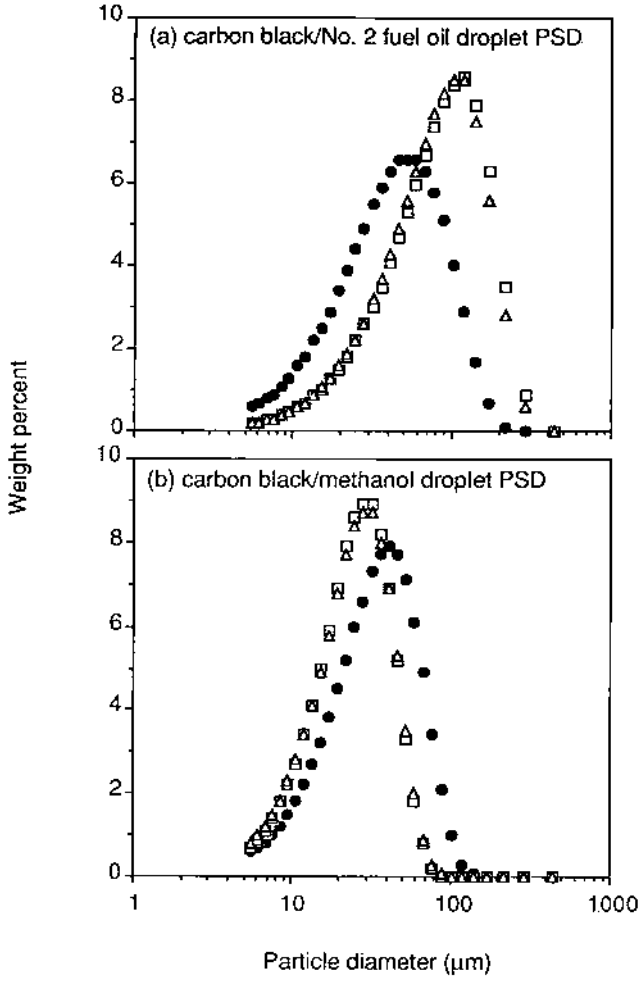

Figure 3 Fuel slurry droplet particle size distributions produced by the fuel–slurry air atomizing injector. (a) Carbon black–fuel oil mixtures: ●, No. 2 fuel oil; □, 47 wt% carbon black–53 wt% fuel oil; △, 50 wt% carbon black–50 wt% fuel oil. (b) Carbon black–methanol mixtures: ●, methanol; □, 42 wt% carbon black–58 wt% methanol; △, 45 wt% carbon black–55 wt% methanol

with the pneumatic atomizer. A small secondary pilot flame (28.3 l min^{-1} natural gas, 331.6 l min^{-1} air) was established at a location perpendicular to the burner flow to provide an ignition source (see *Figure 1*). Next the combustion air, slurry and atomizing air flows were established. Finally, after a stable flame was visually confirmed, the pilot flame was shut off. All six samples tested produced stable self-sustaining flames.

Figures 4, *5* and *6* present the CO, NO and characteristic combustor temperatures, respectively, measured for the six samples tested as functions of excess air values ranging from 0 to 55%. A combustor load of 58.6 kW was maintained for all tests. CO and NO concentrations are presented dry, corrected to 0% oxygen. Combustor temperatures have not been corrected for radiation effects. Comparison of CO emissions (*Figure 4*) between the base case No. 2 fuel oil and methanol tests and their corresponding carbon black slurries indicates similar behaviour. No difference was seen in CO emission between the base case fuels and slurries. With excess air values greater than 5%, CO emissions were consistently less than 50 ppm for all samples tested. These emissions are similar to those produced by the combustion of a medium volatile pulverized bituminous coal in a dry bottom boiler[21].

Figure 7 presents particulate emissions taken from four samples. These data are presented dry as measured (20% excess air). In contrast to the CO data, the particulate data show significant differences between the base case fuel and carbon black slurries. While No. 2 fuel oil and methanol produce particulate emissions of 0.75 and 0 mg dm^{-3}, respectively, the two carbon black No. 2 fuel oil and carbon black–methanol slurries examined produce substantially increased particulate emissions of 40 and 28 mg dm^{-3}, respectively. Presumably, these increased emissions are the result of incomplete carbon burnout. For comparison, uncontrolled combustion of a medium volatile pulverized bituminous coal in a dry bottom boiler at 50% excess air with a nominal 10% ash content would produce particulate emissions of approximately 500 mg dm^{-3} (Ref. 21).

In contrast to the increased particulate emissions shown in *Figure 7*, combustion of the slurry samples produced reduced emissions of NO compared to the base case fuels. *Figure 6* shows that at 20% excess air, NO emissions from the carbon black slurries are approximately half of the emissions from the corresponding base case fuels (50 versus 105 ppm for No. 2 fuel oil, and 15 versus 30 ppm for methanol). Also, the NO emissions for the slurries are less dependent on

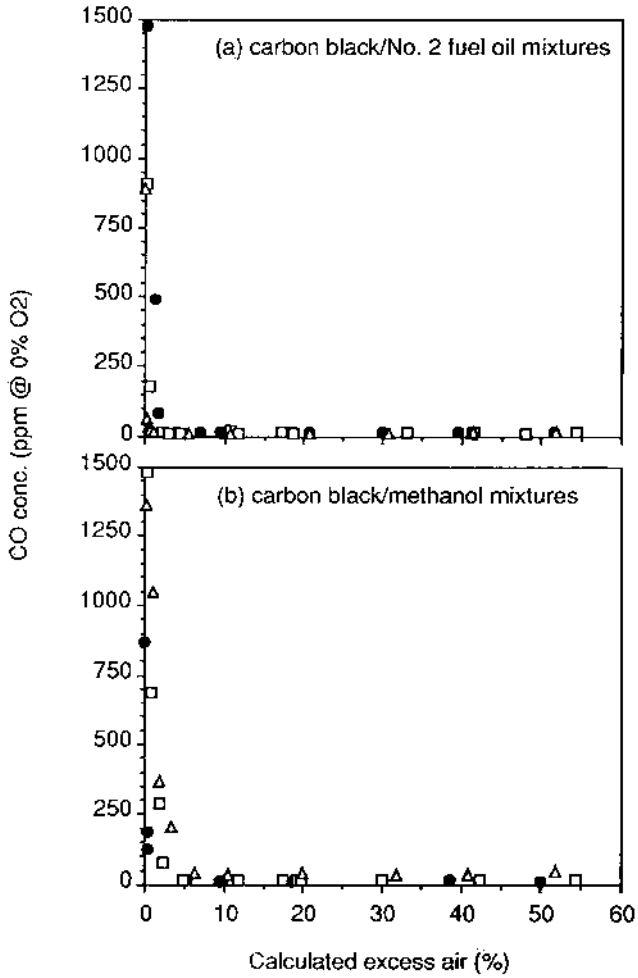

Figure 4 Carbon monoxide emissions versus excess air for six fuel–slurry mixtures. (a) Carbon black–fuel oil mixtures: ●, No. 2 fuel oil; □, 47 wt% carbon black–53 wt% fuel oil; △, 50 wt% carbon black–50 wt% fuel oil. (b) Carbon black–methanol mixtures: ●, methanol; □, 42 wt% carbon black–58 wt% methanol; △, 45 wt% carbon black–55 wt% methanol

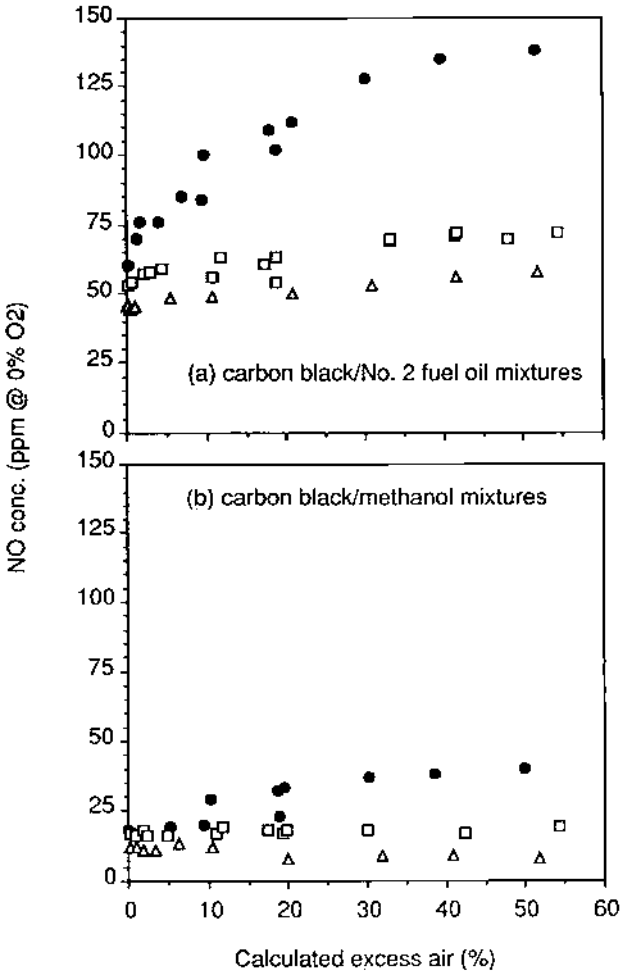

Figure 5 Nitric oxide emissions versus excess air for six fuel slurry mixtures. (a) Carbon black fuel oil mixtures: ●, No. 2 fuel oil; □, 47 wt% carbon black 53 wt% fuel oil; △, 50 wt% carbon black 50 wt% fuel oil. (b) Carbon black methanol mixtures: ●, methanol; □, 42 wt% carbon black 58 wt% methanol; △, 45 wt% carbon black 55 wt% methanol

excess air levels compared to the base case fuels. Since carbon black and methanol contain no fuel bound nitrogen, and No. 2 fuel oil contains very little (approximately 0.02 wt%), it is unlikely that mechanisms involving fuel bound nitrogen are responsible. However, the presence of carbon black likely acts to delay combustion and heat release rates, thereby limiting peak temperatures and thermal NO formation. Uncontrolled combustion of a medium volatile pulverized bituminous coal in a dry bottom boiler at 50% excess air would produce NO emissions of approximately 750–1250 ppm depending on the fuel nitrogen content[21].

CONCLUSIONS

Of the 12 samples proposed for testing, six samples, including base case No. 2 fuel oil and methanol, and two mixtures, each of carbon black–No. 2 fuel oil and carbon black–methanol, were suitable for combustion experiments. These slurries with carbon black contents of up to 50 and 45 wt%, respectively, were pumped and atomized by means of a peristaltic pump and air atomizing scheme and burned in an 82 kW laboratory combustor. Higher carbon black concentrations were examined, but were not pumpable, nor were any of the carbon black–water mixtures tested. Measurements of slurry spray droplet size distributions indicated mean droplet diameters of approximately 100 and 30 μm for the carbon black–No. 2 fuel oil and carbon black–methanol mixtures, respectively. Particulate emissions from the combustion of slurries containing 47 wt% carbon black in No. 2 fuel oil and 42 wt% carbon black in methanol were approximately 40 and 28 mg dm^{-3}, respectively. These particulate emissions are significantly higher than corresponding emissions from the base case No. 2 fuel oil and methanol tests (0.75 and 0 mg dm^{-3}, respectively) and likely result from incomplete carbon burnout. However, in spite of the increased particulate emissions, CO emissions from all tests were similar (less than 50 ppm dry, corrected to 0% oxygen, for furnace stoichiometric ratios of 1.05 or greater). In addition, at 20% excess air, NO emissions from the combustion of the carbon black–No. 2 fuel oil and carbon black–methanol (50 and 15 ppm, respectively) were significantly lower than those measured from the combustion of No. 2 fuel oil and methanol (105 and 30 ppm, respectively).

The results from these experiments indicate that, compared to conventional liquid fuels, carbon black slurries are difficult to pump and atomize, and produce

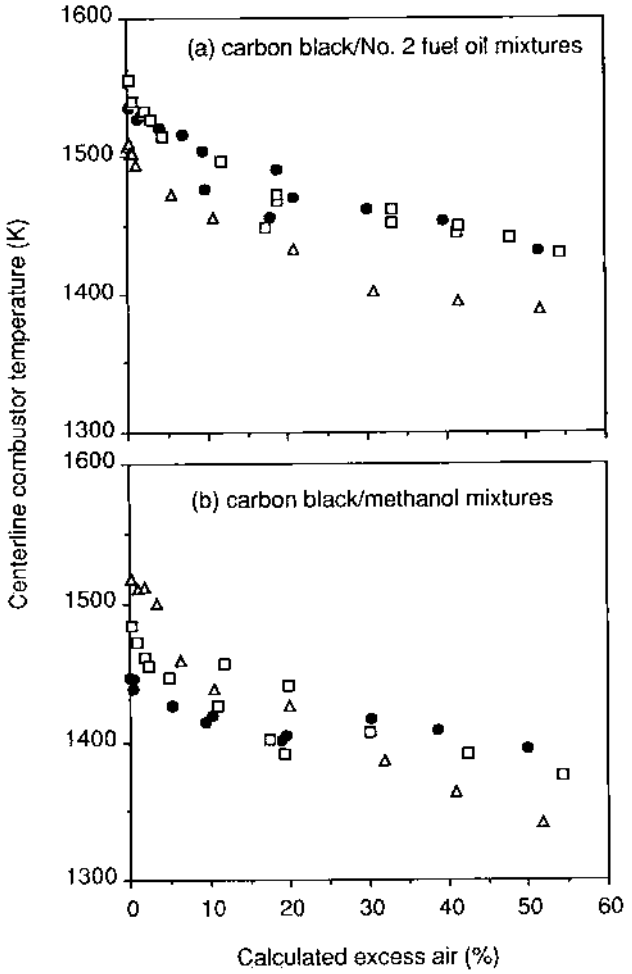

Figure 6 Unshielded centreline combustion chamber temperature versus excess air for six fuel–slurry mixtures. (a) Carbon black–fuel oil mixtures: ●, No. 2 fuel oil; □, 47 wt% carbon black–53 wt% fuel oil; △, 50 wt% carbon black–50 wt% fuel oil. (b) Carbon black–methanol mixtures: ●, methanol; □, 42 wt% carbon black 58 wt% methanol; △, 45 wt% carbon black 55 wt% methanol

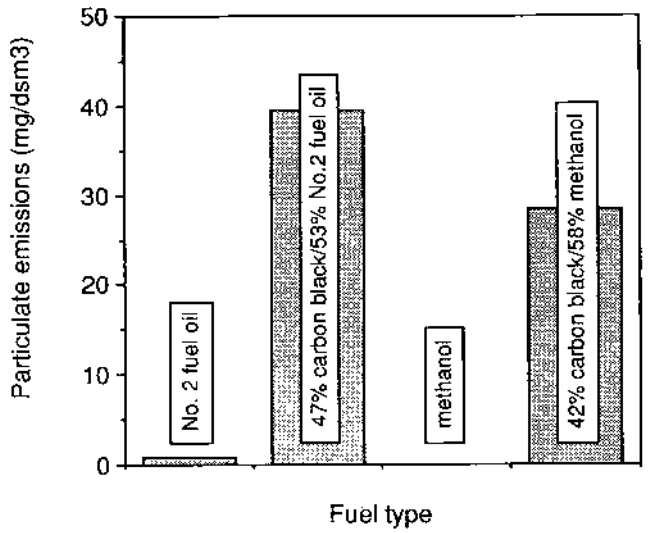

Figure 7 Particulate emissions for four fuel slurry mixtures (20% excess air)

significantly increased particulate emissions. However, measured NO emissions were notably lower compared to the same liquid fuels and particulate emissions were 10 times less than those from comparable pulverized coal combustion. Although not examined here, the use of dispersants, stabilizers and modifications to the pumping and atomization equipment could improve the burning characteristics of carbon black slurries.

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