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On the Burning of Sawdust in a MILD Combustion Furnace

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The purpose of this work is to extend the applicability of moderate or intense low oxygen dilution (MILD) combustion to solid biomass fuels. A laboratory-scale furnace fitted with a parallel jet burner was operated in conventional nonpremixed flame mode, and in MILD combustion mode, using either natural gas or pine sawdust particles. Sawdust with particle sizes in the range of 212−355 μm were injected into the furnace using either air, CO_2, or N_2 as a carrier gas. Measurements of in-furnace wall temperatures and exhaust gas emissions of O_2, CO, NO_x, and ash are presented, together with visual observations at the burner exit region. It was found, through detailed comparisons, that MILD combustion was established without air preheat for both gaseous and solid fuels, suggesting that the parallel jet burner system is suitable for MILD combustion. A 3-fold reduction in NO_x emissions and an increase in CO were recorded during the transition from conventional to MILD combustion using natural gas. The optimal equivalence ratio (ϕ) to reduce both CO and NO_x emissions, when burning sawdust, was determined to be in the range of ϕ = 0.71−0.75, with CO_2 as the carrier gas, and at $\phi \approx 0.75$, with N_2 as the carrier gas. Ash content analysis showed that the extent of carbon burnout was low, which is thought to be due to the relatively short furnace residence times.

Introduction

Heat and exhaust gas recirculation is an innovative approach to create a distributed reaction zone, slow the chemical reaction, and increase the net radiant heat flux (and, thus, thermal efficiency). It is now well-established that a mixture of reactants diluted with combustion products, at a temperature above that of autoignition, can achieve the desired outcome of reduced pollutant emissions and enhanced thermal efficiency. The application of these principles to practical systems has taken different routes, and different names were used to describe the process. Some relied on a descriptive form of the resulting combustion process, i.e. flameless oxidation, whereas others described the features of the reactants streams, i.e., high temperature air combustion. The term used in this paper is moderate or intense low oxygen dilution (MILD) combustion.[1] A good volume of work has been published on MILD combustion, which was reviewed in a recent book.[2] Gaseous, liquid, and solid fuels were investigated and some commercial products are now available.[3,4] Further application of this combustion mode to waste-to-energy technologies is also being investigated.[5]

Despite the above, this relatively new field has many unresolved issues that require further attention and consideration. Some of those issues relate to air preheating and its impact on the system thermal efficiency. Dally's group has proven unequivocally through a series of papers,[6−14] as also reported below, that air preheat is not needed and strong internal recirculation provide a simpler and effective alternative. Tied to this is the location and approach to injecting the reactants into the furnace to achieve MILD combustion. This issue is particularly crucial for solid fuels and, to the authors' knowledge, has not been resolved thus far. What follows is a brief summary of the current knowledge of MILD combustion under gaseous conditions, as well as sample

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findings from a parallel jet burner, which is being applied to solid fuels in this study.

On the fundamental side, Dally et al.[6,7] have investigated the detailed structure of hydrocarbon jet flames issuing into a hot and diluted co-flow to emulate MILD conditions. They used advanced laser diagnostics techniques to investigate the interaction of turbulence and chemistry and provided valuable experimental data to modelers of these flames.[8] Medwell et al.[9,10] extended this work to investigate the effects of fuel type on flame stability and lift-off height and provided an insight on the evolution of the OH radical and the formaldehyde intermediate to better understand the autoignition phenomenon prevalent in these flames. The outcomes of this work have informed the design and testing of a parallel jet burner and helped explain the stability mechanism and major differences with normal diffusion flames.

On the application side, Dally et al.[11] used a recuperative MILD combustion furnace to investigate the effect of fuel type on the stability and characteristics of the flames. They found that premixing the fuel with an inert gas, which simulates exhaust gas recirculation to the fuel jet, helps achieve the MILD conditions without the need for high jet momentum. They also found, through computational studies, that the dilution with inert gas helps shift the stoichiometric contour to the high scalar dissipation region within the jet, which suppresses flame propagation and leads to a distributed reaction further downstream.

Szegö et al.[12,13] investigated the NO_x emission from a 20 kW MILD combustion furnace. They found that air preheating is not required to achieve MILD combustion, even with 40% of the useful heat being extracted through the cooling loop. Based on 191 different measurement cases covering different fuels and dilution levels, they found that neither kinetics nor mixing controls the scaling of NO_x emissions. They concluded that the effects of both mixing and chemistry must be included in any model to predict NO_x emissions in the MILD regime accurately. This work has opened the door to further application of this design to other fuels and conditions and provided insight into the recirculation pattern and how it can be best utilized for solid fuels. Work such as that of Mi et al.[14] has also explored further avenues, using the same geometry, to better optimize the fuel injection and investigate its impact on the thermal efficiency and pollutant emissions.

Work on liquid and solid fuels have also been reported by others. Weber et al.[15] reported on the combustion of both light and heavy fuel oils in high-temperature air. They found that excessive soot and pollutant emissions were prevalent and concluded that specific atomizers should be developed for this process. Very few publications are available on the use of solid fuels, including biomass under MILD conditions. Orsino et al.[16] carried out experimental work on the use of pulverized coal under MILD conditions. They found that coal gave similar heat flux characteristics as gaseous and liquid fuels. They also reported NO_x levels in the range of 250−350 ppm_{vd}. They concluded that there is a great potential to utilize the MILD technology for solid fuels. Suda et al.[17] investigated the combustion characteristics and emission from a cylindrical furnace operating with pulverized bituminous and anthracite coal with preheated air. They found a decrease in ignition delay, enhanced rate of volatiles release, and up to a 40% reduction in NO_x emissions with an increase in the preheated air temperature. Zhang et al.[18] reported on a new burner design for boiler applications, which relies on a two-stage preheating process termed Primary Air Enrichment and Preheating (PRP). They found that, for petroleum coke and anthracite coal fuels, a stable flame was established and a 50% reduction in NO_x emissions was measured when compared to low NO_x burners.[19] From the above, it is clear that (i) MILD combustion has great potential to be utilized for solid fuels and (ii) very little data are available on how it can be best implemented.

The use of biomass as a fuel for energy generation has been identified in many countries around the world as one of the strategies to reduce the dependency on fossil fuels. In a recent paper, Demirbas[20] reviewed the combustion characteristics of different biomass fuels and concluded that biomass has great potential to reduce emission of pollutants and help provide CO_2-neutral energy systems. He also found that premixing of biomass with coal has similar potential. Blasiak and Yang[3] reviewed the latest developments in using MILD combustion for oxy-fuels, coal under volumetric combustion and cofiring of coal with biomass. In particular, they investigated the advantages of using Rotating Opposed Fired Air (ROFA) to enhance mixing and internal exhaust gas recirculation in boilers. They found that, by incorporating the high-momentum jets, through the ROFA system, it was possible to mix different ratios of coal and biomass and run the boiler with 100% biomass. Similar to others, they have also reported a reduction in NO_x and CO for all of the fuel mixtures they used. Wang et al.[21] reported on a computational study that compares the emissions and performance characteristics of the Flameless Oxidation and Continuous Stage Air Combustion (COSTAIR) technologies applied to coal and biomass (straw) fuels. The technologies were applied to a 12 MW_e coal-fired, CFPC power plant, using the ECLIPSE simulation software. They found that both technologies have the potential to reduce NO_x emissions by up to 90% and that, although straw emits less pollutants, it has a slightly lower efficiency than coal-fired plants.

The above discussion clearly indicates that there is a need for further work in applying MILD combustion to solid fuels, because of its excellent potential to reduce emissions, especially when biomass is being considered. Hence, in this paper, we report on an experimental study that examines the use of sawdust, as a fuel, in a MILD combustion furnace. The effect of the carrier gas and the operating parameters on the stability and characteristics of the combustion, as well as the exhaust gas emissions, are discussed and analyzed. For a fixed fuel flow rate, the effects of equivalence ratio (ϕ) and type of carrier gas are investigated with the temperatures and exhaust gas emissions being measured and compared.

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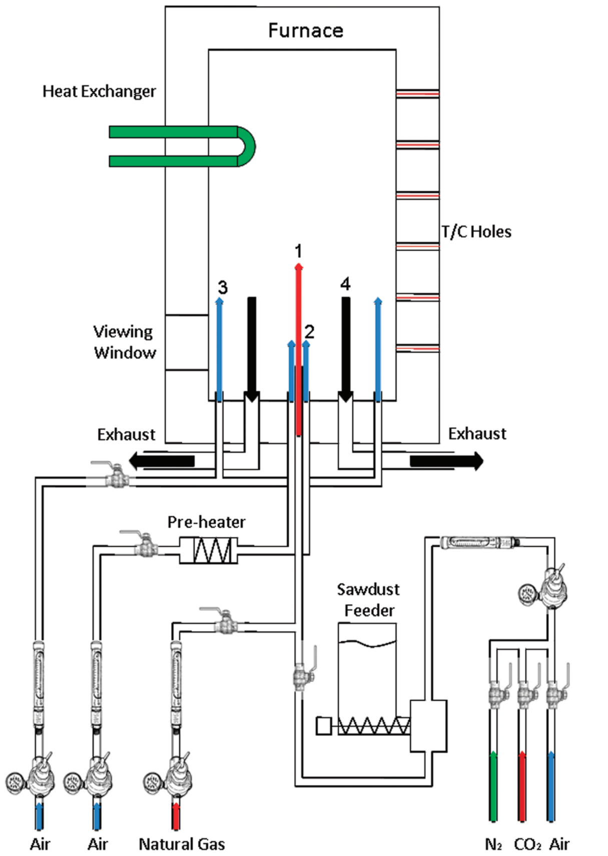

Figure 1. Schematic diagram of the MILD combustion furnace and supply system.

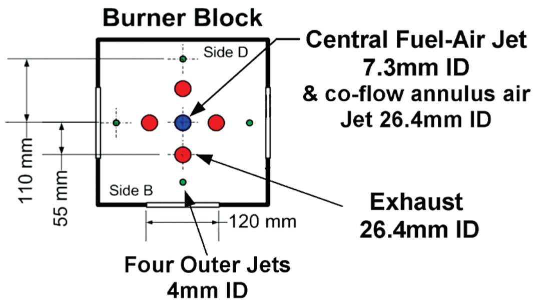

Figure 2. Burner block showing the arrangement of the fuel and air delivery jets and exhaust ports.

Experimental Setup

In this study, a laboratory scale MILD combustion furnace (MCF), shown in Figure 1, is used. This furnace was built and instrumented by Szegö et al.[13] In this work, the fuel jet diameter was increased to 7.3 mm to suit sawdust fuel. The furnace has a square cross section of 280 mm $\times$280 mm and a height of 585 mm and is lined with high-temperature ceramic fiberboard refractory. The furnace flow diagram is shown in Figure 1. The furnace is preheated to temperatures above that of autoignition, using a nonpremixed natural gas flame. According to Origin Energy Australia, the composition of the natural gas was 91.4% CH_4, 4.4% C_2H_6, 2.1% CO_2, and 1.3% N_2, with the remainder being higher-order hydrocarbons (C_xH_y).

The switch to MILD mode was achieved once the furnace wall temperature exceeded 950 °C. The burner block and jet arrangement at the bottom of the furnace is shown in Figure 2. The central fuel nozzle, with an internal diameter of 7.3 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 (see notations 1 and 2 in Figure 1). The combustion air through the central air nozzle (Figure 1, notation 2) is gradually switched to the four surrounding nozzles, which have an internal diameter of 4 mm (Figure 1, notation 3). Sawdust replaces natural gas in the central fuel nozzle and is carried into the furnace using air, CO_2 or N_2. The mass flow rate of sawdust and carrier gas was set independent of each other.

The furnace was equipped with a cooling-loop heat exchanger, which was supplied with water at a constant inlet temperature and flow rate. The U-shaped cooling loop was positioned at a height of 292.5 mm above the burner plane and had an exposed surface area of 0.015 m^2. The combustion air was preheated to 440 °C using an electric heater during the preheating stage only. As soon as MILD combustion was achieved, the heater was switched off and ambient-temperature air was used. The air heater was only used to accelerate the preheatimg of the furnace.

The mole fractions of O_2, CO, and NO_x in the exhaust were measured using a TESTO Model 350XL portable gas analyzer. The absolute errors of these measurements, according to the manufacturer's specifications, are ±0.8% (by volume) for O_2, ±5% (by volume) for CO, and ±5 ppmv for NO_x. The internal temperature of the furnace was measured at the centerline, at a distance 542.5 mm from the bottom. The exhaust gas temperature was measured at a distance of 100 mm from the exhaust inlet. The inlet air temperature was measured 400 mm from the inlet to the furnace. Wall temperatures were 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 and using four 75-μm-diameter bead Pt/Pt13%Rh (R-Type) thermocouples located at 142.5, 242.5, 342.5, and 442.5 mm. The last four wall-temperature measurement locations are referred to as Wall #1, Wall #2, Wall #3, and Wall #4, respectively. All temperature measurements were logged once every 3 s using a PC and USB-TC data logger. Radiation correction for temperature requires an elaborate algorithm to consider all of the surfaces inside the furnaces and will change, depending on the location of the thermocouple. Since only the temperature of one wall was measured, we are unable to correct for radiation effects on the thermocouple measurements without adding large uncertainties. Because the temperature data are used in this paper for comparison purposes, rather than to introduce additional uncertainties to our temperature measurements, radiation corrections were not performed.

Sawdust Fuel. Sawdust from pine milling was dried and reduced in size in the present work. The raw sawdust had an average moisture content of 4.7%−7.3% before it was dried in an oven set at 120 °C. The sawdust was then milled and sieved into two size ranges, which had diameters of $d \leq 212$ and 212 μm $< d \leq 355$ μm. Only the larger size fraction was used in this study. The apparent density of these larger particles was 432 kg/m^3. The effect of sawdust particle size was the subject of a previous study,[23] and those results are briefly summarized here. The study used the same furnace and operating conditions considered here and tested the temperature, emission, and stability of MILD combustion for two particle sizes, namely, $d < 106\,\mu$m and $106\,\mu$m $< d < 355\,\mu$m. In this work, the furnace was operated with a thermal input of 7.5 kW, $\phi = 0.7$, and CO_2 was used as the sawdust carrier gas. The NO_x emission was determined to be on the same order (~80 ppm) for both small and large particles. Similarly, the CO emission was measured at 12 ppm in the exhaust. It was also observed that MILD

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Table 1. Analysis of Sawdust

	value
analysis	
C	50.4 wt % db
H	6.1 wt % db
O[a]	42.5 wt % db
N	0.22 wt % db
S	0.02 wt % db
ash	0.9 wt % db
moisture	2.0 wt %[b]
gross dry calorific value, GDCV	18.1 MJ/kg

[a] Balance. [b] Wet basis.

combustion was achieved with no visible flames and semiuniform temperature distribution. Based on these data, larger-sized particles were used in the present study.

The elemental analysis of the sawdust fuel is given in Table 1. A sawdust 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 DC motor controlled the amount of sawdust, which was fed into the feeding chamber. The carrier gas was set at constant flow rate and carried the sawdust into the furnace. The carrier gas flow rate was sufficiently high to carry the sawdust through the supply tubes and provide the required momentum inside the furnace. Alternative methods, e.g., conventional cyclone-based particle feeders, are not able to provide such control without major changes in the feeder design. The average feeding rate of the sawdust was relatively constant and fluctuated by less than ±3.4% over a period of 5 min. A sketch of the feeder system is shown in Figure 1.

Results and Discussion

MILD Combustion with Natural Gas. Szegö et al.[12,13,22] designed and tested the MILD Combustion Furnace (MCF) for gaseous fuels. They reported temperature measurements and flue-gas composition from conventional and MILD flames using compressed natural gas (CNG) and liquefied petroleum gas (LPG) as fuels. In their setup, the fuel in the MILD mode was injected through the four periphery jets (Figure 1, notation 3), while the air was injected through the central air jet (Figure 1, notation 2). Hereafter, this configuration will be termed "old". In the current work, the same burner block was used except that the fuel was supplied through the central nozzle (Figure 1, notation 1), while the combustion air was injected through the periphery jets. Noteworthy is that the jet diameters were increased, e.g., the central jet from a 5 mm ID to a 7.3 mm ID and the four periphery jets from a 2 mm ID to a 4 mm ID. These new burner jet sizes have produced similar results, when using natural gas as fuel, to those reported earlier by Szegö et al.[22] A comparison of the operating conditions and measurement results obtained for the conventional, new configuration, and old configuration is shown in Table 2.

The switch from the old configuration to the new configuration caused an increase in CO emission but had little impact on NO_x emissions. Noteworthy is that the CO emission did not exceed 300 ppm, which is well below the allowable legislative limits.

Figure 3 shows the measured temperature time history at the bottom and top sections of the furnace as well as the temperature of the exhaust gases and combustion air for the MCF using natural gas (new configuration) at a capacity of 7.5 kW. It is clear that the transition to MILD combustion reduces the temperature gradient along the height of the furnace from 170 to 90 °C and slightly changes the exhaust gas temperature. Also noticeable is that turning off the primary air preheater has only a minor effect on the furnace temperatures. The flame attached to the center jet's bluff body become invisible during the transition between conventional mode and MILD mode, as shown in Figure 4. Worthy of note, is that the soot which appears on the bluff-body's surface is only a feature of the heating up process and is due to imperfect distribution of the coflow air. When operating in MILD mode this coflow is not used and the bluff-body is retracted to be level with the burner block.

Since the same operating features of the MILD mode were noted in the work of Szegö et al.,[13,22] this parallel jet burner configuration and the separation distance between the jets clearly seems to represent a good combination and gives further evidence of the flexibility and applicability of the current concept to be retrofitted to existing furnace systems. It is important to realize that MILD combustion can be achieved, for the same equivalence ratio as that for conventional combustion, by simply altering the mixing process within the furnace.

Figure 5 shows the time history of the wall temperatures at four different locations inside the furnace. The switch to MILD combustion helped homogenize the furnace temperatures, reducing the overall temperature spread from ~200 °C to ~130 °C. The switch to MILD mode also causes a temporary reduction (40 °C) in measured temperatures at locations Wall #1 and Wall #2. These thermocouples are located 142.5 mm and 242.5 mm above one of the periphery jets, so it is believed that the room-temperature air stream is cooling these thermocouples. The walls of the furnace play a key role in heat exchange with the furnace gases and, in turn, preheating the primary air. Additionally, for MILD combustion to be sustained, the mixing of air and fuel with recirculated products acts to increase the mixture temperature above the autoignition temperature. The fluctuations in temperature measured at Wall #2 are associated with measurement noise of this particular thermocouple, while the profile and trend remain consistent with the other three measured profiles.

A time history of the mole fractions of O_2, CO, and NO_x in the exhaust for the natural gas fuel at 7.5 kW are shown in Figure 6. The plot shows that the switch from a conventional configuration to MILD mode caused a 3-fold drop in NO_x emissions , while the CO amount has increased markedly to ~800 ppm. This sudden increase in CO emission during the transition is consistent with other measurements in MILD combustors using gaseous fuels.[24,25] The equivalence ratio for these conditions was $\phi = 0.77$. Increasing the air supply caused the CO amount to be reduced; at $\phi = 0.62$, the levels had been reduced below detectable limits. This suggests that the CO increase is related to the effects of mixing inside the furnace, rather than oxygen levels. Szegö et al.[22] also measured very low CO emissions for cases with higher equivalence ratios ($\phi \approx 0.90$). No attempt was made to reduce the diameter of the periphery jets to test this hypothesis.

Reducing the equivalence ratio increases the NO_x levels only slightly, with levels remaining at < 30 ppm. Scaling the NO_x to 3% O_2 shows little difference in the NOx levels.

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Table 2. Comparison of Operating Parameters and Resulting Emissions for Conventional and MILD Combustion Modes Using Natural Gas as the Fuel

combustion mode	conventional	MILD new configuration	MILD old configuration [13]
thermal input (kW)	7.5	7.5	7.5
equivalence ratio, ϕ	0.71−0.77	0.77−0.62	0.8
central fuel jet velocity (m/s, avg)	4.78	4.78	0
periphery jet velocity (m/s, avg)	0	53.5−66.4	16.11
central air jet velocity (m/s, avg)	19.92−18.36	0	17.7
CO in the exhaust (ppmv dry)	< 10	350−14	< 10
NO_x in the exhaust (ppmv dry)	70	22−30	27

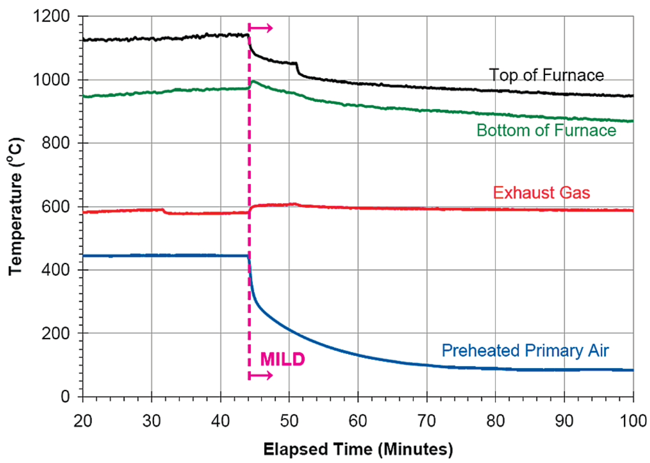

Figure 3. Temporal variations of the measured temperatures for the MILD combustion furnace operating on natural gas with a 10 kW heat input.

MILD Combustion with Sawdust. Three different experiments were conducted using sawdust fuel for three different carrier gases, namely, air, CO_2, and N_2. The sawdust particle size was in the range of 212−315 μm for all cases. The furnace was operated with a heat input capacity of 10 kW, while the heat exchanger removed ~2.5 kW of heat from the furnace. The following analyzes the experimental results from each of the case studies.

Sawdust Carried by Air. The sawdust carried by air was supplied through the centerline jet, while the rest of the air was supplied through the four surrounding jets. This setup is not ideal for MILD combustion, because the presence of air in the same jet as the fuel, which is undergoing fast pyrolysis due to the high furnace temperature, can lead to undesired localized reactions and the appearance of flame sheets.

A summary of the operating conditions for sawdust with air as the carrier gas is shown in Table 3. Within this table and in the proceeding tables, Mode 1 refers to conditions with a constant carrier gas supply and varying combustion air flow rates, while Mode 2 denotes a constant combustion air supply with varying carrier gas flow rates. The feeding rate of sawdust remained constant, for a fixed heat input, and was independently controlled. The air supply in the central jet, compared to the total air supply, was varied during the experiments. It was found that the measured CO levels were ~13 ppm in the exhaust and insensitive to the central jet momentum. The global equivalence ratio was also changed from ϕ = 0.88 to 1.0 by changing the total air flow rate. The measured CO and NO_x concentrations were determined to be insensitive to this change and similar values were recorded for all equivalence ratios measured. The average measured NO_x concentration was 120−130 ppm for all cases.

The higher levels of NOx in these experiments are consistent with visual observations inside the furnace. Regardless of the relative distribution of air flow between the central and periphery jets, faint flame sheets, which were hardly visible, were always present. Such flame sheets are associated with conventional and high-temperature combustion, which is associated with increased NO_x formation. Figure 7 shows photographs of typical sawdust combustion with air as the carrier gas, taken from a side window close to the bottom of the furnace for 7.5 kW[22] and 10 kW. The photographs show that (i) multiple intermittent flame sheets exist, especially close to the centerline fuel jet exit, and (ii) hot burning particles are circulating inside the furnace. The relationship between the increased level of NO_x and the appearance of the flame sheets has been reported earlier for gaseous fuels with partially premixed air.[11] Noteworthy is the fact that these flames were visible throughout the tested range of equivalence ratios for both thermal inputs (7.5 kW and 10 kW).

The measured temperature distribution inside the furnace for these cases are typical to those measured earlier for gaseous fuels under MILD combustion conditions. On average, the difference in the temperature between the top and bottom section of the furnace was ~160 °C, while the average mixture temperature in the furnace was ~1000 °C. The exhaust gas temperature was measured to be ~600 °C for all cases.

Sawdust Carried by CO_2. Carbon dioxide (CO_2) was used to carry the sawdust to the central jet of the furnace. A summary of the operating parameters and resulting measurements for the combustion of sawdust using CO_2 as the carrier gas is shown in Table 4. In this experiment, the combustion air was injected only through the four periphery nozzles, while the CO_2 carried the sawdust through the central nozzle. A variety of equivalence ratios and nozzle injection velocities were studied, with the exhaust emission being measured for all cases. It was found that the CO levels were generally higher in these experiments than the previous case with air as the carrier gas. For an equivalence ratio of ϕ = 0.86, the measured CO levels were ~800 ppm but decreased to 235 ppm at ϕ = 0.75 and decreased further to 100 ppm at ϕ = 0.71. Further increasing the air supply did not result in further reductions in CO. The reason behind the increase in CO emission, relative to changes in the carrier gas, is not well-understood. The chemical reaction pathway is expected to be more complex than simple gaseous fuels; nonetheless, fast pyrolysis and invisible flames (gaseous combustion) create conditions that are not dissimilar to gaseous combustion. Hence, it is speculated that the increased CO emissions is caused by a combination of (1) the increased concentration of CO_2 (carrier gas) and, hence, a reduction in the rate of CO oxidation, (2) the ~100 °C reduction in average furnace temperature, and (3) a change in mixing pattern inside the furnace. Detailed modeling studies are currently underway to understand this specific issue.

The measured NO_x emissions from these flames are observed to be smaller than that for the air-carrying case.

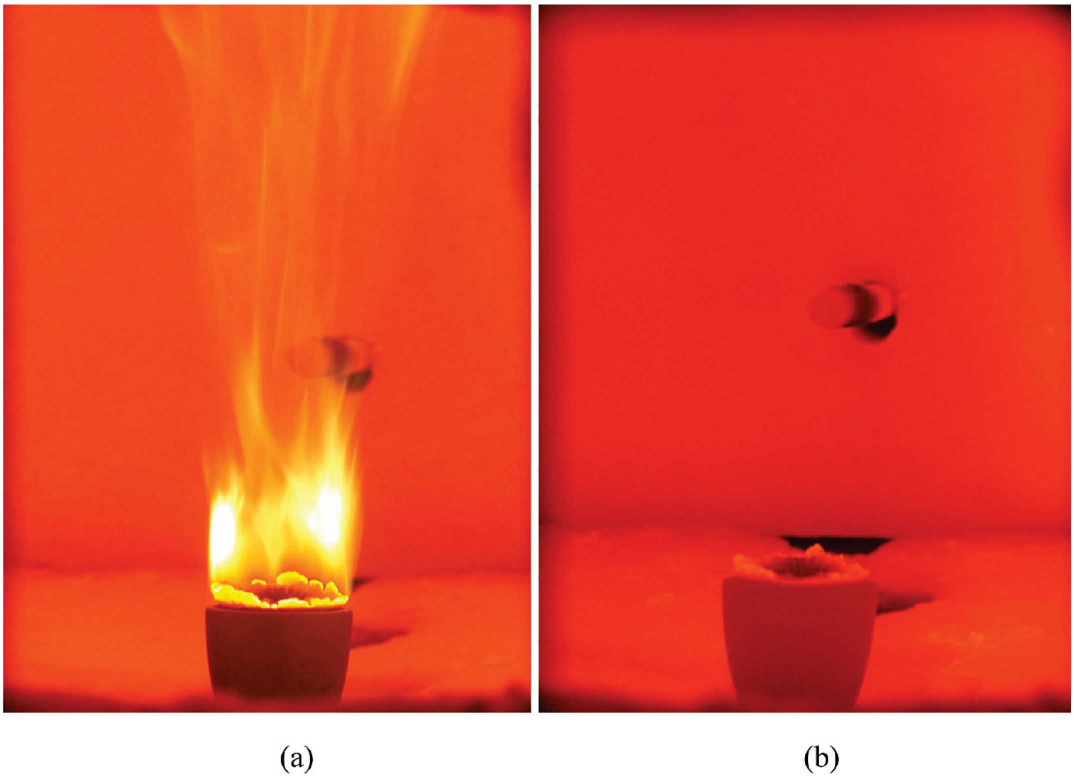

Figure 4. Photographs of the central jet and bluff body in the burner block within MILD combustion furnace operating on natural gas with a 10 kW heat input for (a) conventional combustion and (b) MILD combustion.[22].

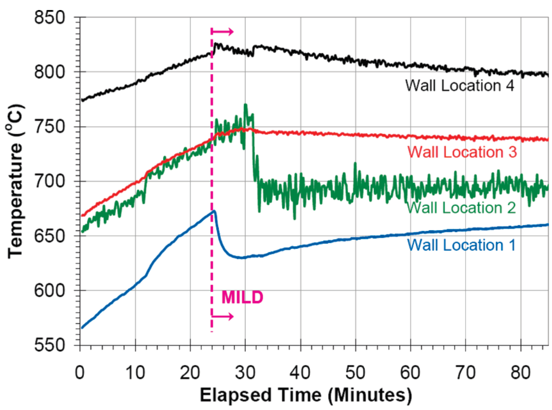

Figure 5. Wall temperature measurements at different heights within the MILD combustion furnace operating on natural gas with a 10 kW heat input.

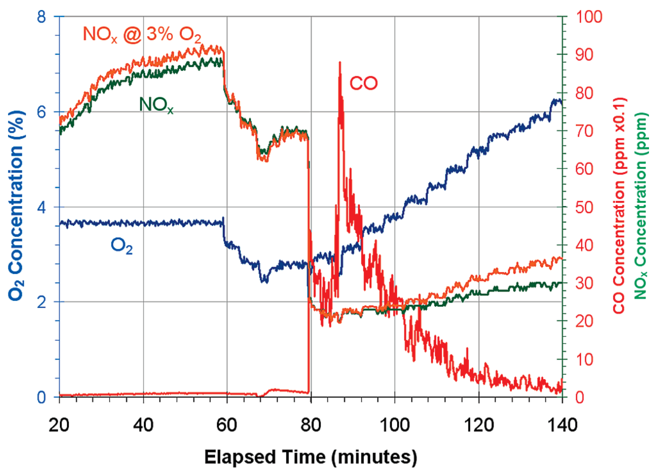

Figure 6. Temporal variations of O_2, CO, and NO_x measured in the exhaust for natural gas combustion under conventional and MILD modes, under different equivalence ratio conditions.

The measured NO_x concentration for all the conditions listed in Table 4 was <110 ppm. In particular, for an equivalence ratio of ϕ = 0.75, the NO_x measurements were 78 ppm. Figure 8 shows a photograph of the inside of the furnace during sawdust combustion using CO_2 as the fuel carrier gas. Figure 8a represents the 7.5 kW firing rate case and shows no visible flame. Figure 8b represents the 10 kW firing rate case and shows hot glowing particles that have fallen to the bottom of the furnace. Intermittent flame sheets were also present in this experiment. Residence time clearly plays an important role in establishing MILD combustion and subsequent pollutant emissions. This issue is further discussed later in this paper.

The measured gas temperatures at the top and bottom of the furnace had a difference of <110 °C for most cases. This suggests that the higher levels of CO_2 in the furnace enhance the radiation exchange and contribute to a more uniform

Table 3. Operating Parameters and Resulting Emissions for MILD Combustion Using Sawdust Carried by Air

parameter	mode 1	mode 2
thermal input (kW)	10.0	10.0
mass flow rate of sawdust (g/s)	0.5525	0.5525
sawdust carrier gas	air	air
equivalence ratio, ϕ	0.88−1.0	0.94−1.0
central air jet velocity (m/s)	39.87	41.19−31.84
periphery air jet velocity (m/s)	33.19−22.35	29.38
CO in the exhaust (ppmv dry)	13	13
NO_x in the exhaust (ppmv dry)	120−130	120−130

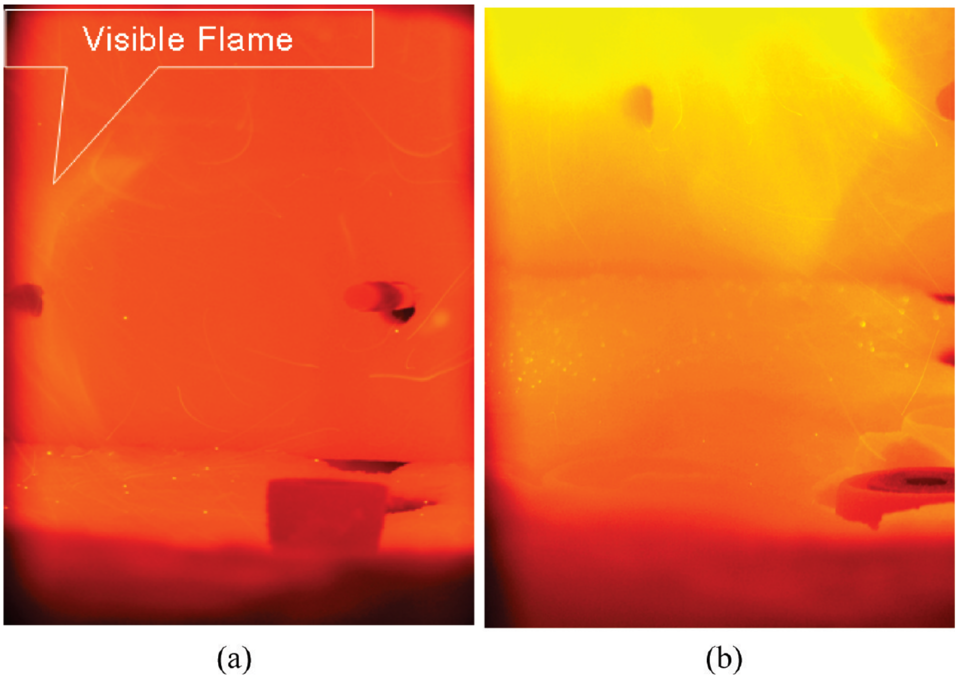

Figure 7. Photographs of the bottom of the furnace when operating under MILD conditions with sawdust carried by air with heat inputs of (a) 7.5 kW and (b) 10 kW.

Table 4. Operating Parameters and Resulting Emissions for MILD Combustion Using Sawdust Carried by CO_2

parameter	mode 1	mode 2
thermal input (kW)	10.0	10.0
mass flow rate of sawdust (g/s)	0.5525	0.5525
sawdust carrier gas	CO_2	CO_2
equivalence ratio, ϕ	0.86−0.71	0.71
CO_2 center jet velocity (m/s)	12.68	11.34−16.10
periphery air jet velocity (m/s, avg)	67.9−87.29	82.41
CO in the exhaust (ppmv dry)	800−100	100
NOx in the exhaust (ppmv dry)	110−78	78

temperature throughout the furnace. In addition, the difference in the wall temperatures at the top and bottom parts of the furnace was < 200 °C, with an average wall temperature of 800 °C.

Sawdust Carried by N_2. In this experiment, N_2 was used as the carrier gas. Similar experiments to those presented for the two previous cases were conducted, with the operating conditions and resulting measurements summarized in Table 5. The measured CO concentration was determined to be up to one order of magnitude lower than those measured for the two previous cases. For the equivalence ratio of ϕ = 0.75 case, the measured CO level was 19 ppm and increased to 280 ppm by ϕ = 0.8. The CO emissions were observed to be independent of the central jet velocity at a fixed sawdust supply rate (Mode 2 tests).

The measured NO_x emissions were determined to be < 90 ppm, similar to the CO_2 carrier case, which was reduced to 70 ppm with decreasing periphery air flow rate to achieve ϕ = 0.80. However, for ϕ = 0.75, the measured NO_x emissions were reduced to ~30 ppm. For this latter condition, increasing the N_2 in the furnace through the central jet caused NO_x emissions to increase back to ~70 ppm.

With similar equivalence ratios and with N_2 as the carrier gas, very faint flame sheets appeared occasionally in the furnace for the 10 kW case, while, for the 7.5 kW case, *no* visible flame was noticed.

In Figure 9, the temperature profile over time is shown for gases at the top and bottom of the furnace, as well as for the exhaust gas and primary air temperature. The furnace clearly has a steady temperature profile, with a difference of < 200 °C. Comparing the temperature profiles under MILD conditions for sawdust with those for natural gas (in Figure 3), sawdust maintains a consistent temperature gradient inside the furnace, similar to natural gas, even after the primary air preheater has been turned off. This implies a reasonably uniform mixing pattern, combustion process, and heat release from the sawdust within the furnace.

Discussion

From the data presented above, MILD combustion conditions clearly are achievable in a laboratory-scale furnace without the need for air preheating for both gaseous and solid fuels. Figures 5 and 6 also clearly show that mixing plays a crucial role in reducing emissions and providing the semiuniform thermal field associated with the MILD combustion regime. The flexibility in the way fuel is introduced, at least for the gaseous fuel case, has provided further encouraging evidence that this technology can be easily adapted to existing combustion systems.

One of the main factors that is common among the three sawdust cases considered in this study is the effect of residence time. The calculated residence time for these cases is summarized in Table 6. In this table, the residence time of the supplied gaseous streams was calculated using the volume method, in parentheses, and the furnace length method. The volume method relies on the ratio of the "fuel" stream volume flow rate, compared to the furnace volume, while the furnace length method simply relies on the ratio of twice the furnace length divided by the "fuel" stream velocity. Because of the recirculating nature of the flow field inside this furnace, and the different burnout time (which is due to the different carrier gases), the particle residence time is hard to estimate. Note that the gaseous

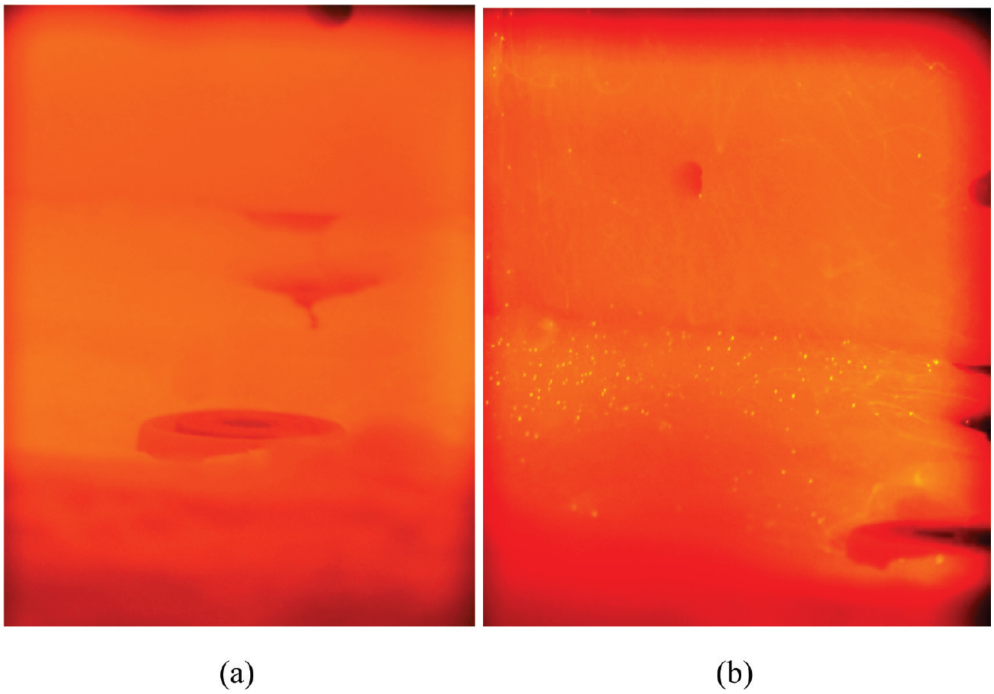

Figure 8. Photographs of the bottom of the furnace when operating under MILD conditions with sawdust carried by CO_2 with heat inputs of (a) 7.5 kW and (b) 10 kW.

Table 5. Operating Parameters and Resulting Emissions for MILD Combustion Using Sawdust Carried by N_2

parameter	mode 1	mode 2
thermal input (kW)	10.0	10.0
mass flow rate of sawdust (g/s)	0.5525	0.5525
sawdust carrier gas	N_2	N_2
equivalence ratio, ϕ	0.71−0.80	0.75
N_2 center jet velocity (m/s)	19.66	17.88−15.94
periphery air jet velocity (m/s)	87.29−77.46	82.63
CO in the exhaust (ppmv dry)	19−280	19
NO_x in the exhaust (ppmv dry)	~85	30

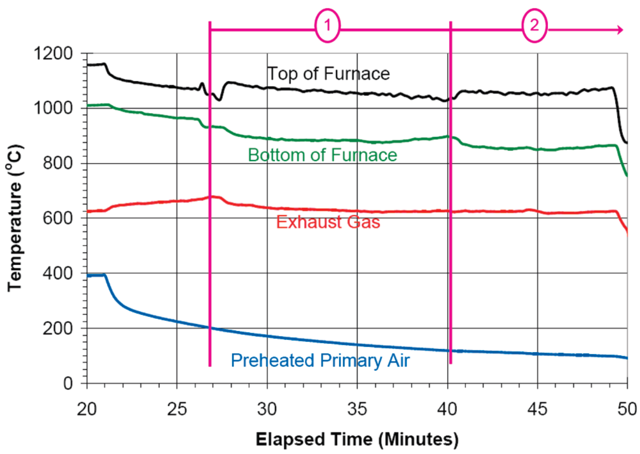

Figure 9. Temporal variations for the top and bottom of the furnace, the primary air, and the exhaust gases for the furnace operating under MILD conditions with N_2 carrying sawdust with a 10 kW heat input. Mode 1 has a constant N_2 supply and variable air supply, whereas Mode 2 has a constant air supply (ϕ = 0.75) and variable N_2 velocities.

residence time is not too different for the two thermal inputs considered in this study. For the higher thermal input case (10 kW), an increase in the pyrolyzed hydrocarbons, as well as char, is inevitable. The diluted conditions and short residence time seem to lead to the appearance of flame sheets and burning particles on the floor of the furnace. A slight increase in CO emissions was also observed, which is consistent with the measurements reported by others for gaseous fuels.[22,24]

Figures 7 and 8 provide a clear point of differentiation between the 7.5 kW case, where the particle burnout time is less than its residence time, and the 10 kW case, where the opposite is true. For the 10 kW case, the particles were circulated back to the furnace floor quicker than they could burn and they can be seen to glow red on the furnace floor. Although we are not able to calculated the particle's residence time, the gaseous residence time can provide an indication of the relative change in the particle residence time between the cases, which is consistent with our observation.

The results also show a major difference in emission and flame visibility for the different cases studied, particularly the effect of the carrier gas. Using N_2 as the carrier gas produced the least amount of CO and NO_x in the exhaust, despite the fact that N_2 causes a slight reduction in the furnace temperature. Worth noting is the fact that the difference in heat capacity of CO_2 and N_2 is ~200 J/(kg K) and the average mass flow rate of the carrier gases is ~1 g/s. This implied that the difference in heat capacity plays a minor role in the difference in temperature inside the furnace, especially that the heat input is 10 kW.

The case with air as the carrier gas gave the worst results, in terms of CO and NO_x emissions. The reason behind this phenomenon is related to the conditions required to establish MILD combustion. The separation of the fuel and oxidant to allow initial mixing with hot products inside the furnace is an essential condition to achieve MILD combustion. This condition can be relaxed if a very high momentum of the fuel/oxidant jet is used. Although this may be achievable in gaseous fuels, it is quite hard to apply to solid fuels, because it will require substantial air flow rates and/or reduced jet diameter,

Table 6. Flame Visibility and Calculated Residence Time, Using the Furnace Length Method and the Volume Method, for the Different Cases Investigated in the Study

		7.5 kW Case			10.0 kW Case		
fuel	carrier gas	flame visibility	residence time (s)	volume method	flame visibility	residence time (s)	volume method
natural gas		not visible	0.49	vol. 70	not visible	0.65	vol. 53
sawdust	air	visible	0.16	vol. 60	visible	0.12	vol. 57
sawdust	CO_2	not visible	0.13	vol. 48	visible	0.18	vol. 45
sawdust	N_2	not visible	0.12	vol. 41	visible	0.13	vol. 39

Table 7. Measured Ash Content and CO Emissions for Various Carrier Gas Cases for a 10 kW Sawdust Input

sawdust carrier gas (10 kW heat input)	ash yield (% db)	CO emissions (ppm)
air	83.6	13 ($0.88 < \phi < 1.0$)
CO_2	52.0	800 ($\phi = 0.86$)
N_2	59.3	280 ($\phi = 0.80$)

which is not favorable for particle dispersion and pyrolysis inside the furnace.

The mechanism of NO_x formation is difficult to determine, based on the available data. Szegö et al.[12] used the same MCF operating with gaseous fuels to examine the NO_x formation mechanisms. They have considered 193 cases where the NO_x emissions were measured and related to the operating conditions. They have found that the existing scaling laws do not apply to this combustion mode and that it is likely that a combination of parameters must be considered before the dominant NO_x mechanism can be established.

The char for the three different carrier gases studied in this work was collected and analyzed for moisture and ash content. These results are presented in Table 7 with the measured CO emissions for each of the studied cases. The ash yield results indicate that the case with air as the carrier gas gives the best carbon burnout, with an ash yield of 83%, while the cases with CO_2 and N_2 show lower extents of burnout with ash yields of 52.0% and 59.3%, respectively. The extent of carbon burnout in all these tests is low and could be explained by the relatively short residence times of the char in the furnace. No char was collected for the 7.5 kW case, where the residence time of the fuel particles is likely to be longer and the emitted CO also was determined to be lower. This relationship between carbon burnout and the emission of CO is evident when considering the third column of Table 7.

Note that, despite the relatively low carbon burnout, the NO_x and CO emissions are quite low, in comparison with many conventional systems burning similar fuels. However, direct comparison is not possible, because of the varied conditions used in MILD combustion. Also, the char burnout is affected by many parameters that are unlikely to be equivalent in any standard combustion system. Further research is required to verify the effect of residence time on carbon burnout and the resulting emissions in this system.

Summary and Conclusions

This paper reports on the successful burning of natural gas and sawdust in a laboratory-scale furnace operating under the moderate or intense low oxygen dilution (MILD) combustion regime. The sawdust was carried into the furnace using three different gases (namely, air, CO_2, or N_2). MILD conditions were achieved for all cases operating with natural gas and no flame was visible for any of the cases considered; however, for the sawdust, the use of air as the carrier gas resulted in faint flame sheets appearing inside the furnace, resulting in NO_x emissions of up to 130 ppm. When the carrier gas was either CO_2 or N_2, MILD combustion was achieved except that faint flame sheets did appear for the higher firing rate of 10 kW. No air preheating was needed in any of the cases studied, suggesting that the parallel jet burner allows initial mixing with hot products, for both gaseous and solid fuels.

NO_x emissions in natural gas combustion can be reduced by more than 3-fold using the MILD regime for the same equivalence ratio, compared with conventional combustion. However, CO emission increased markedly in the MILD regime and more air was needed to minimize the CO emission.

When using air as the carrier gas of the sawdust, minimal CO and fixed carbon were emitted from the furnace, while higher NO_x emissions was measured in the exhaust. This is attributed to the flame sheets observed in the furnace, which are a sign of high-temperature conventional combustion and the associated higher thermal NO_x formation.

For the case of sawdust carried by CO_2, it was found that NO_x emissions dropped to 70% of that measured for the case using air as the carrier gas. These low levels are similar to those of natural gas under MILD combustion. The CO emissions, in the case of CO_2 as the carrier gas, was higher than that for the air or N_2 cases. This is consistent with the observed lower carbon burnout and is based on the ash yield of the char. The high CO emission can be attributed to the increased concentration of CO_2 and the ~100 °C reduction in average furnace temperature. Both factors lead to slower CO oxidation rates and, hence, higher CO concentrations in the exhaust. The optimal range of operation to reduce CO and NO_x emissions, when CO_2 is the carrier gas, is given as $\phi = 0.71-0.75$.

By far, the lowest CO and NO_x emissions measured were for the case with N_2 as the carrier gas. For $\phi = 0.75$, the measured CO was only ~19 ppm, while the NO_x was as low as ~30 ppm. These values remained almost unchanged, even when altering the equivalence ratio in the furnace. The ash yield measured for this char was 59.3%, which indicates that carbon burnout is slightly better than that for the CO_2 case, but considerably less than that for the air case.

The wall temperature distribution inside the furnace became quite uniform under MILD conditions. It was noticed that this uniformity is also correlated with the reduction of NO_x emissions, because it reduces peak temperatures that can cause NO_x formation. This uniformity was further enhanced in the CO_2 case, because of its radiation characteristics.

Ash yield analyses showed that, for the 10 kW case, a reduction in carbon burnout was determined to be highest for the air case and lowest for the CO_2 case. This was consistent with the level of CO found in the exhaust.