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Low-oxygen enrichment in coal-fired utility boilers

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ABSTRACT

The benefits of oxygen enrichment have been demonstrated in a variety of industrial combustion applications, such as glass melting, steel reheating furnaces, cement/lime kilns, etc. To date, no long-term industrial-scale implementation of oxygen enrichment in boilers has been reported, primarily due to their already high thermal efficiencies, and to the very large scale of these systems – requiring significant amounts of oxygen.

In recent years, the topic of oxygen combustion in boilers has experienced a strong comeback, due to the appearance of new drivers. Oxygen enrichment is an effective tool in reducing emissions, and in using low-calorific fuels. Additionally, the increasing interest in carbon capture and sequestration has made the concept of a full oxygen-fired boiler more of a reality, since power generation produces around 30% of the greenhouse gases.

This paper analyzes the use of low-oxygen enrichment in boilers, in terms of operational and economical impact. A literature review of the impact of oxygen in coal-fired systems is presented. Several technological solutions for the low-oxygen enrichment operation are proposed and accompanied by numerical simulation results. In addition, results of comprehensive low-oxygen enrichment tests performed on a 1.5 MW pilot boiler using Illinois coal are reported, including the impact of oxy-combustion on a variety of pollutants, such as NO_x and unburnt carbon in ash. Finally, the paper presents the economical aspects related to the technology. It is concluded that the oxy-fired operation may represent an economical way to lower the cost of power generation.

INTRODUCTION

Combustion of fossil fuels, following a long history, remains today the main source of energy. However, the combustion processes generate harmful emissions, with a significant impact on all aspects of life, ranging from individual health to global climate issues.

As the society's evolution requires larger amounts of electricity - directly linked with the economical growth, there is an obvious need for "Clean Energy." A large effort directed towards this goal has been devoted in the last few decades. As progress in this area is made, regulations become increasingly restrictive, leading to a continuous drive for improvement. The immense amount of time and effort dedicated to Clean Energy has led to significant breakthroughs in a wide range of processes. As an example, the current NO_x emission levels are around 10 PPM in gas turbine applications, and around 100 PPM for coal applications.

One of the significant breakthroughs in combustion applications has been the introduction of oxygen enrichment. This technology has significantly reduced emissions and increased efficiency in a variety of processes, such as glass melting and forming, cement production, metals, etc. Oxygen addition to the process, or complete replacement of the combustion air introduces several challenges, as well as rewards. The production rate of the process can be significantly increased (15-25% commonly achieved in glass, cement, reheating furnaces, etc.), and the fuel efficiency can be increased (25-35% for glass furnaces). At the same time, the overall emissions have been reduced dramatically when using oxygen enrichment, or full oxygen firing. Thus, the NOx emissions in high temperature furnaces such as glass melters have been reduced by orders of magnitude. A potentially huge impact of oxygen enrichment is the possibility to concentrate carbon dioxide in the flue gases, and thus to allow its capture, in order to limit greenhouse-gas emissions. This is considered to be a more cost effective CO_2 capture technique than the alternative method of flue gas scrubbing with chemical reagents. The issue of carbon dioxide capture has prompted the development of several revolutionary concepts in power generation (Mathieu and Nihart 1999**,** Horbaniuc *et al*. 2001, Marin *et al*. 2001, etc.).

The introduction of oxygen in power systems has been limited to date, in spite of a large R&D effort, due to the already high thermal efficiency in boilers, and the very high excess air levels in gas turbines, where mass flow rate is crucial for these large power systems. In addition, these power systems would require large amounts of oxygen, altering the process economics. At the same time, new developments in oxy-combustion technology make oxygen enrichment more attractive than ever, with great opportunities for process improvement.

Today's power generation situation, particularly in the United States, increases the applicability of oxygen enrichment in power generation installations. Around 50% of the power produced in the US is based on coal, and is produced in aging plants, with overall efficiencies around 30%. An increasing share of the power is generated today from natural gas combined-cycle systems, and around 95% of the new projected capacity relies on natural gas. The increased consumption of natural gas has led to a large jump in the price of natural gas. Given these factors, increasing the efficiency of the power generation and/or the throughput of the existing coal-fired units may be very attractive, particularly using low-emission technologies.

This effort will focus primarily on the analysis of coal fired power generation, under low oxygen-enrichment conditions. The traditional advantages of oxygen enrichment are enhanced combustion – primarily for low-BTU fuels, or low volatile coals, increased production, lower emissions of carbon monoxide, unburnt fuel, NO_x, etc. Different low-oxygen enrichment techniques, specific to coal-fired boilers, will be described. Experimental results of these techniques in a 5 MMBTU coal-fired pilot boiler will be presented, and the results will be analyzed. The paper concludes that the low-oxygen enrichment technologies applied to coal-fired boilers represents an efficient means to enhance the power generation process.

IMPACT OF OXYGEN ENRICHMENT ON COAL COMBUSTION

Coal combustion is a complex process, separated into two important stages, namely devolatilization and char oxidation. The impact of oxygen enrichment on both processes is addressed below.

1. Devolatilization process

Marin *et al.* (2002a) describe the impact of oxygen enrichment on the coal devolatilization process. Thus, Charon (1988) analyzes the impact of oxygen concentration on the duration of the volatile combustion, for a high-volatile coal with a size of 200-250 µm, in a 1273 K furnace. Figure 1 presents the variation of the volatile combustion time as a function of oxygen concentration. The results show a strong effect for oxygen levels of 10 to 30%. While the duration of the process continues to decrease for increasing oxygen concentrations, the variation slows down significantly. This may indicate that, in order to speed-up the combustion process, low oxygen enrichment represents an efficient means, as is shown below.

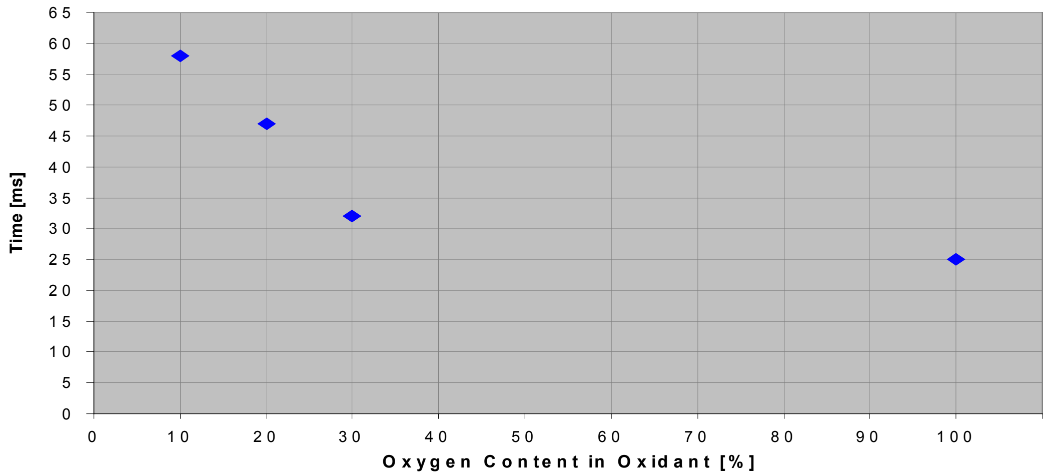

Figure 1. Duration of volatile combustion as a function of oxygen content.

2. Char Oxidation

The impact of oxygen enrichment on char oxidation is well documented in literature, as shown by Marin et al. (2002a). The char burnout process is controlled by diffusion mechanisms at high and medium temperatures, and by kinetic mechanisms at low temperatures (Bauer *et al.* 1999). Char oxidation becomes increasingly difficult in late stages of burnout. This phenomenon is due to a reduction in available surface area as well as a drop in the specific reactivity (Hurt *et al.* 1998). Oxygen enrichment has been shown to significantly enhance the char combustion process.

Figure 2 presents the duration of the char combustion, as a function of the oxygen content in the oxidant, in a 1273 K furnace, for a high-volatile coal (Charon 1988). The results show a somewhat different trend from the results in Fig. 1 for the devolatilization process of the same type of coal. While the impact on the devolatilization time varies strongly for low-medium oxygen concentrations, the char burning time decreases steadily as the oxygen concentration increases. Beeston and Essenhigh (1963) show that the impact of oxygen (slope of the char burning time) increases with the particle size, therefore for large particles the presence of oxygen enriched oxidants is more beneficial.

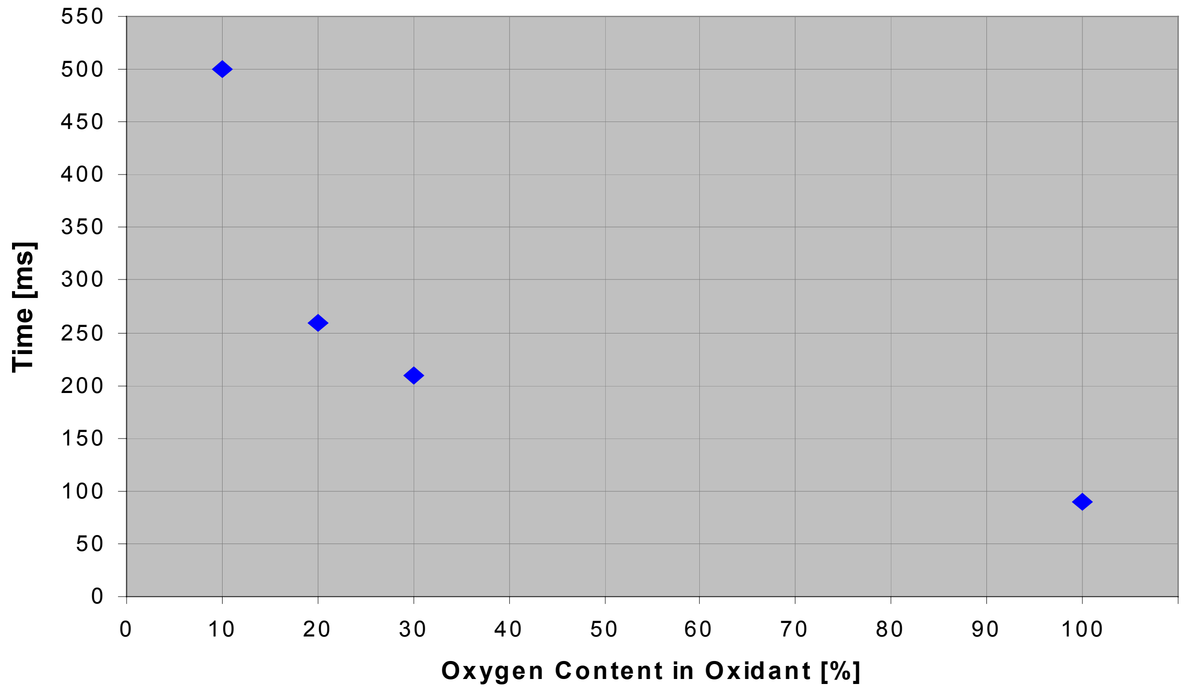

Figure 2. Duration of char combustion as a function of oxygen content.

It can be concluded that oxygen concentration plays an important role in the combustion of coal, in both stages of devolatilization and char combustion. The results presented above indicate that introducing oxygen at the right time and at the right location, even in small quantities, may significantly improve the combustion process. The next section will present several different types of possible oxygen enrichment in boilers, and will discuss the main drivers in implementing such technologies.

LOW OXYGEN ENRICHMENT IN BOILERS

Low oxygen enrichment represents a process where the amount of oxygen introduced increases moderately the overall oxygen content in oxidant. Thus, global concentrations of 22-28% oxygen in oxidant may be referred-to as oxygen enriched combustion (or oxygen boosting). Oxygen boosting is a widely used technology in a variety of high-temperature applications, such as glass melting and forming, steel reheating, aluminum secondary melting, cement making, etc. Processes such as cement making have used oxygen boosting for several decades, for various reasons, including increased production, enhanced efficiency and reduced emissions. For coal-fired kilns in particular, oxygen boosting has been used to increase the use of low-volatile, cheaper alternatives such as pet-coke, and also to decrease the amount of unburnt fuel in the flue gas. The most widely used methods to introduce oxygen in the kiln are:

- Lancing directly in the coal stream, in order to rapidly initiate the combustion process, and to limit the NO_x emissions,
- Lancing between the main burner and the load (cement clinker), in order to contain the enhanced radiative heat transfer impact of oxygen to the kiln walls,
- Global enrichment of the secondary air stream, primarily used for increased production when using high quality fuels.

Numerous publications show the favorable impact of oxygen in coal-fired kilns. Thus, Hoyle *et al.* (1996) show that oxygen leads to production increases of 2.3 to 5.2 tons of clinker per ton of oxygen. It is noted that oxygen enrichment was used in the Germany and Russia in the 1930s and 1940s. In late 1950s, Southwestern Portland and Huron Cement conducted enrichment testing, using lances. The authors state that lancing should be controlled such that the flame be stable, and NO_x be lowered. Oxygen has been introduced via a lance, at a rate of up to 72 t/d, at 100 psi. The oxygen lancing produced a shorter, more intense flame. The study concludes that oxygen decreases kiln and preheater gas volumes, improves the heat transfer and lowers BTU per ton of clinker, reduces pressure loss through the preheater and eliminates the preheater ID fan as a system bottleneck. These conclusions are particularly applicable to boilers.

Marin *et al.* (2002a) show the main characteristics of oxygen enrichment in boilers. The combustion process in pulverized coal-fired boilers is described in Fig. 3. The oxidant (traditionally air) is, in general, split into three streams. The primary air (PA) is used for the coal transport from the pre-processing station into the boiler, and to stabilize the flame. The secondary air (SA) represents 20-80% of the oxidant, and it can be separated into several streams, used for staging the combustion process. Finally, modern combustion systems use a tertiary air stream (TA) (10-30% of the total oxidant) used for deep combustion staging, leading to low NO_x emissions.

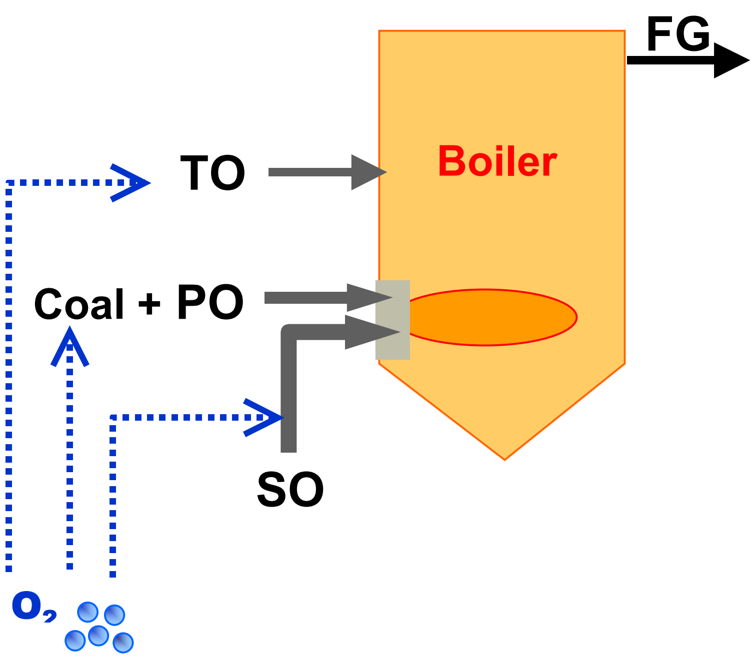

Figure 3. Schematic of the combustion process in a pulverized coal-fired boiler.

All three oxidant streams may be suitable for oxygen enrichment, as shown in Fig. 3, depending on the system requirements. Thus, the primary oxidant stream can be enriched in order to improve the flame stability, and to reduce the NO_x emissions. Thus, the rapid heating of the coal particle reduces the NO formation reaction, by releasing the coal-bound nitrogen in elemental form, rather than nitrous oxide, and thus reduces the fuel NO_x. This process is also aided by the fact that the combustion process at this level is fuel rich, or oxygen lean. The oxygen enrichment of the primary stream is particularly attractive for combustion systems using low-volatile coals, such as pet-coke, and for low-NO_x operation.

The secondary stream oxygen enrichment is of interest for increased throughput, in boilers limited by the ID fan and/or the flue gas post-treatment installation. At the same time, the oxygen-enriched oxidant will lead to improved combustion, with reduced unburnt fuel, and therefore reduced loss on ignition (LOI), the carbon content in ash. By enriching certain oxidant sub-streams, and/or by adjusting the mixing patterns (such as the swirl) between the oxidant and the fuel, reduced NO_x emissions may by also achieved.

Finally, the tertiary stream oxygen enrichment may be an effective emission control, as well as a means to increase the combustion efficiency, by ensuring a more complete fuel combustion. It is well known that, by the addition of a tertiary air stream for low NO_x operation, the combustion process can be negatively impacted, with increased CO and unburnt hydrocarbon emissions, as well as increased LOI. The appropriate introduction of oxygen at this advanced stage in the combustion process will complete the oxidation process, and will preserve the low NO_x operation (Niksa 2001). It is noted that the addition of a tertiary air system in a utility boiler is a complex and expensive endeavor, which may also reduce, as stated above, the process efficiency. The addition of an oxygen delivery system represents a more economical option, avoiding the negative aspects of the tertiary air (large air ducts, additional fans, inconvenient locations, etc.).

The above reflections indicate that oxygen enrichment in boilers may be very beneficial for a variety of reasons, starting with lowered emissions, increased combustion efficiency, and also increased steam generation. This last impact is very relevant for the US power generation. Thus, in the last decade, many boilers have switched from the high-sulfur, high heating value Midwestern coals, to the low-sulfur, low heating value Western coals. In the process, many boilers had to be de-rated significantly, with a resulting loss of power throughput. In addition, the boiler operation during hot summertime days is de-rated by an additional 5-10% due to the low air density. In all these circumstance, the addition of oxygen may supplement the oxidant input, and reduce the specific flue gas volume per unit throughput, thus potentially increasing the power production. Simple calculations show that the production of one MWh of electricity requires an amount of around 0.6 tons of oxygen for a Rankine cycle with an efficiency of around 35%. This number may be used to calculate the amount of oxygen necessary to boost the combustion air with oxygen. For instance, for a 100MW plant, increasing the production by 5% on a continuous basis requires 72 tons/day of oxygen, corresponding to a small air separation unit. It is noted that by introducing oxygen in an efficient way, the overall improvement to the system can be much more significant, as shown below.

EXPERIMENTAL RESULTS

A team consisting of Air Liquide (AL), Babcock and Wilcox (B&W), the Illinois State Geological Survey (ISGS) and sponsored by the Illinois Clean Coal Institute (ICCI) and the Illinois Department of Commerce and Economic Opportunity has conducted a series of experimental tests on the B&W pilot boiler, using Illinois coal. Both low- and high-oxygen enrichment tests have been conducted (Marin *et al*. 2002b). While the high-oxygen enrichment tests are reported in another paper during this conference, the low-oxygen enrichment tests are presented here. Figure 4 shows the schematic of the 1.5 MW (5 MMBTU/hr), pulverized coal pilot boiler of B&W, and the respective locations of the burner, combustion chamber, and the convective sections are shown. The oxygen injection locations are also shown in Fig. 4 – they include the primary and/or secondary air level, both termed hereon "first stage" injection, and the tertiary oxidant level. In order to optimize the location, amount and oxygen injection method into the boiler, extensive computer simulation has been performed prior to the actual implementation.

Figure 5 shows the temperature profile in the boiler as predicted by FLUENT, for the conditions where oxygen enrichment has been implemented at the tertiary oxidant level. The results of the numerical simulation have been used to optimize the oxygen injection location and jet profile, inlet velocity and flow rate into the boiler. The results increased the team confidence that the oxygen implementation in the field will not constitute a safety hazard, that no hot spots will occur, and that the oxygen will be efficiently mixed into the combustion space, and will be consumed in its entirety. The modeling results have been extremely helpful in the course of the project, assisting in the successful completion of the tests. The significance of the modeling effort conducted during this project is clearly emphasized by the experimental results. Thus, a few injectors have been actually implemented in the tertiary oxidant, and selected results are presented in Fig. 6.

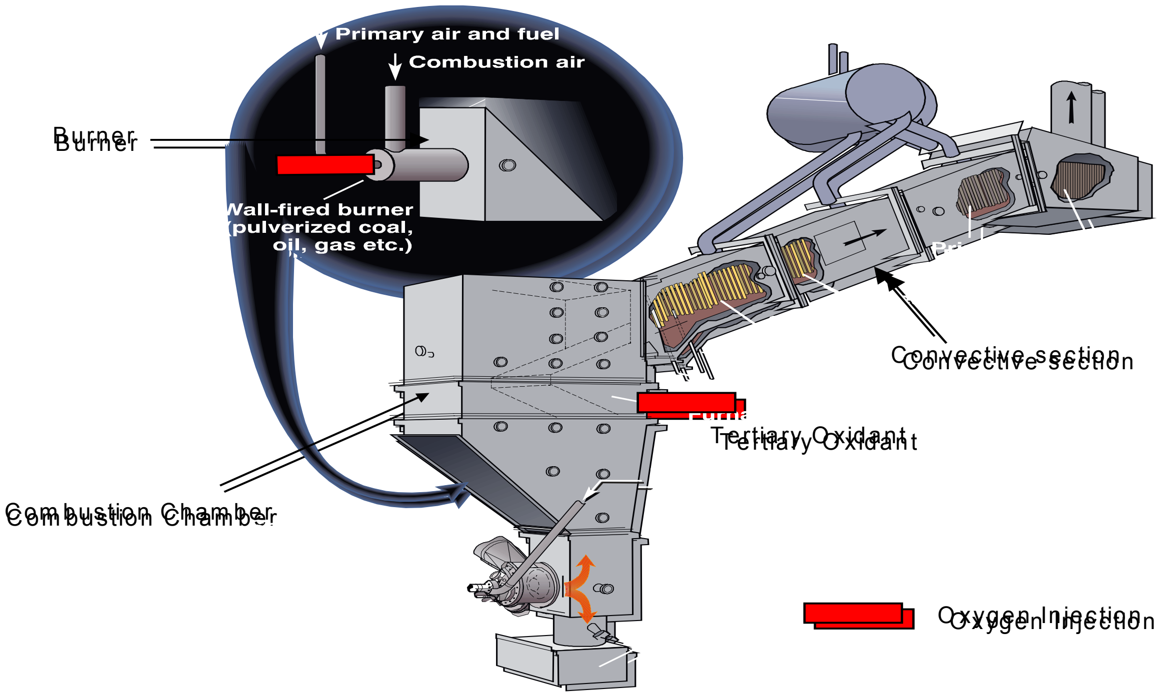

Figure 4. Schematic of the B&W – 5 MMBTU coal fired pilot boiler.

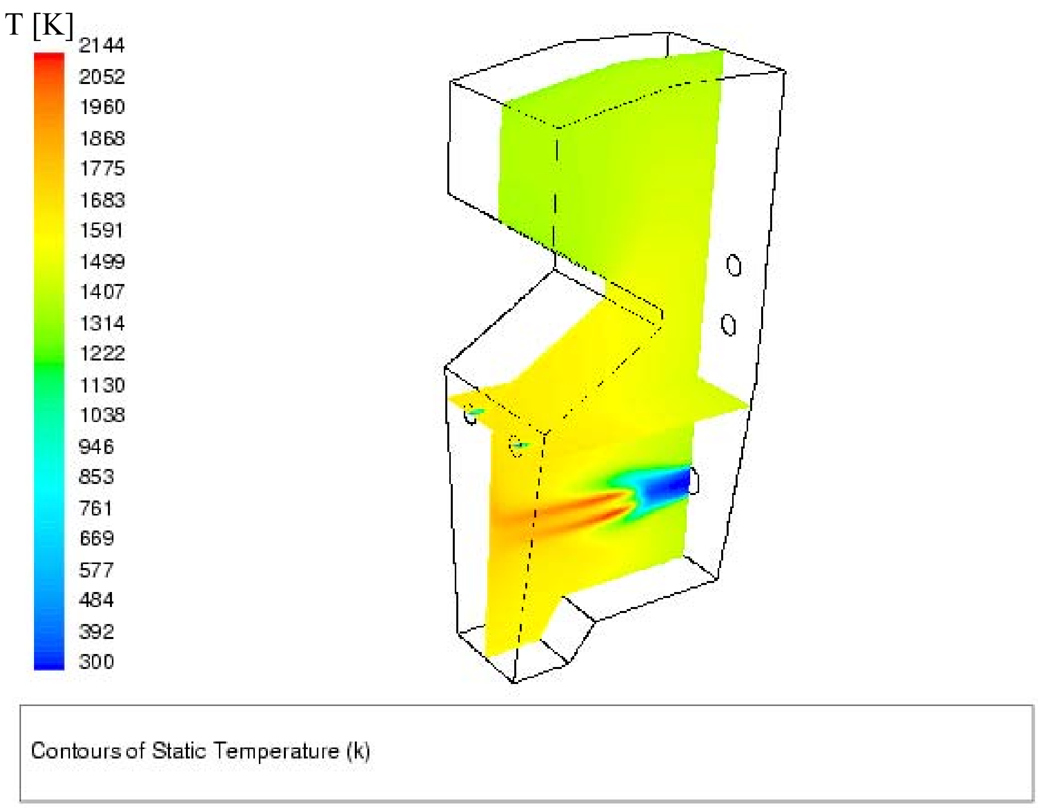

Figure 5. Temperature profile in the combustion chamber using low-oxygen enrichment in the tertiary oxidant level, as predicted by FLUENT.

As mentioned above, the tests conducted during the project included oxygen injection at various locations in the combustion process. This paper only presents selected results, as the data gathered continues to be processed, and additional tests are being planned. Thus, Fig. 6 presents the NO_x emissions resulted from enriching the oxygen at the "first stage" of the combustion process, defined above. The two levels of enrichment – termed as Enrichment 1 and 2, respectively, led to emissions significantly lower than the base case, by 15% and 21% lower, respectively. It is noted that the oxidant at the first stage of combustion contained an enriched oxidant level, obtained by injecting oxygen in the process and removing a determined amount of air, such that the total amount of oxidant be controlled. The decrease in the emissions is attributed to two factors: the first one is linked to the modified combustion characteristics at the burner level, due to the presence of enriched oxidant. The coal particle is heated faster, and the devolatilization/ignition process is altered when compared to air firing, as explained above. The reduced emissions are also attributed to modified mixing patterns at the burner level, due to a modified amount of overall oxidant into the combustion process, therefore different (in fact lower) velocities. The results in Fig. 6 clearly show the impact of oxygen enrichment at the first stage of combustion on the NO_x emissions.

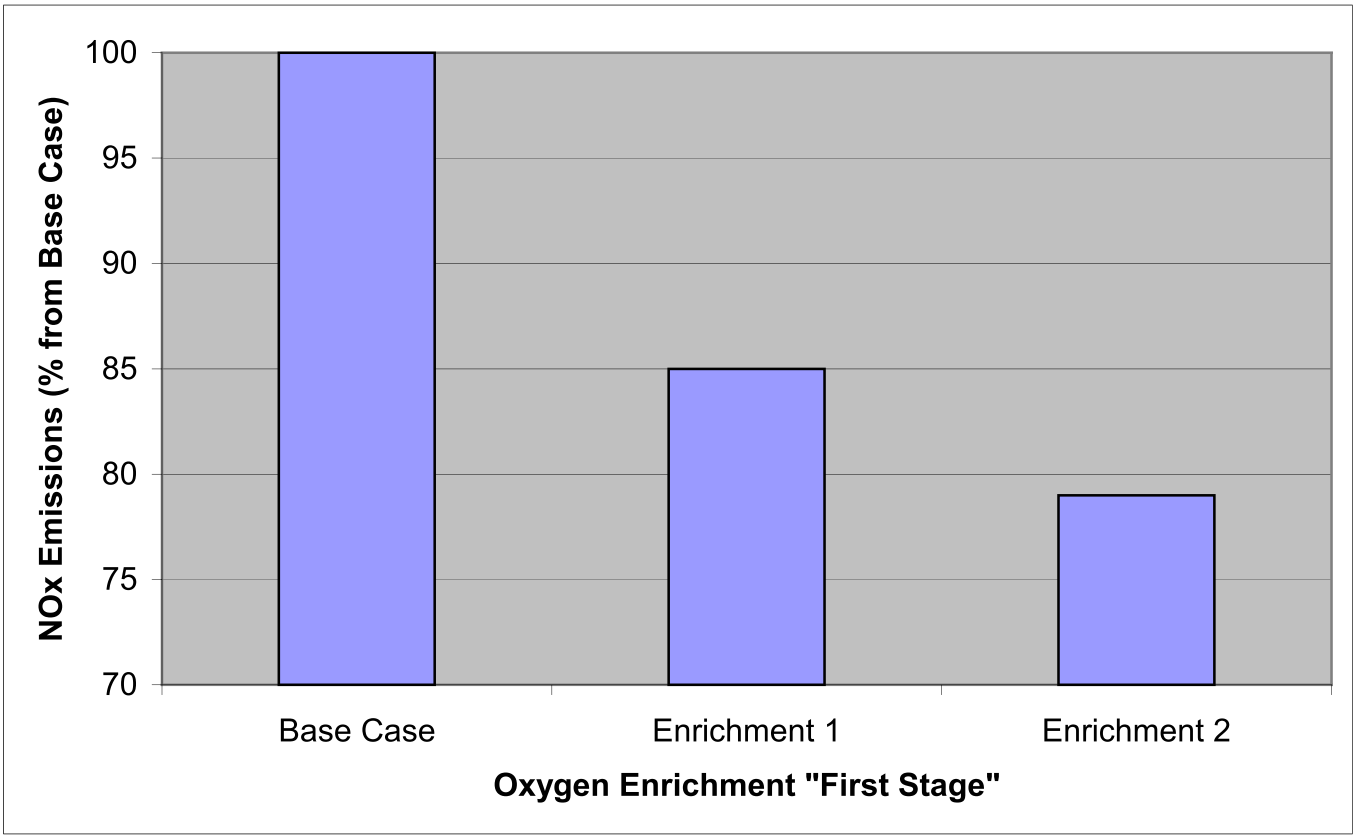

Figure 6. NO_x emissions results using oxygen injection technologies at the first stage of combustion level.

Finally, several tests using oxygen enrichment in the tertiary oxidant have been conducted. Figure 7 shows the NO_x emission results during low-oxygen enrichment operation using two different injector designs in the tertiary oxidant ports, A and B respectively, with different inlet velocities and flow patterns. The results indicate that oxygen boosting at the tertiary oxidant level impacts significantly the boiler emissions, and can be used as a means to control NO_x. The results in Fig. 7 also show that the amount and means to introduce oxygen at this level in the combustion system significantly affect the NO_x emissions, and therefore can constitute an efficient means to control this emission. In addition, the use of oxygen enrichment at this level may have a significant impact on the quality of the combustion process. It is well known that when strong staging is introduced in a combustion process, the overall characteristics of the process can be altered, particularly with respect to unburnt fuel.

Figure 8 presents the loss on ignition (LOI), representing the amount of carbon in the ash, for three cases. The first case represents the base case operation, and the second case represents the case where only air is fired through the tertiary air ports. It is noted that when combustion staging is implemented, the amount of unburnt carbon in the ash increases by around 70%, indicating a deterioration of the combustion process, accompanied by a reduction in NO_x emissions. When oxygen is injected at this level using a quasi-optimized lance, the unburnt fuel is reduced by about 75% compared to air-firing only, and by around 45% when compared to the base case. The NO_x emissions are relatively unchanged when compared to the low-NO_xx operation using tertiary air only.

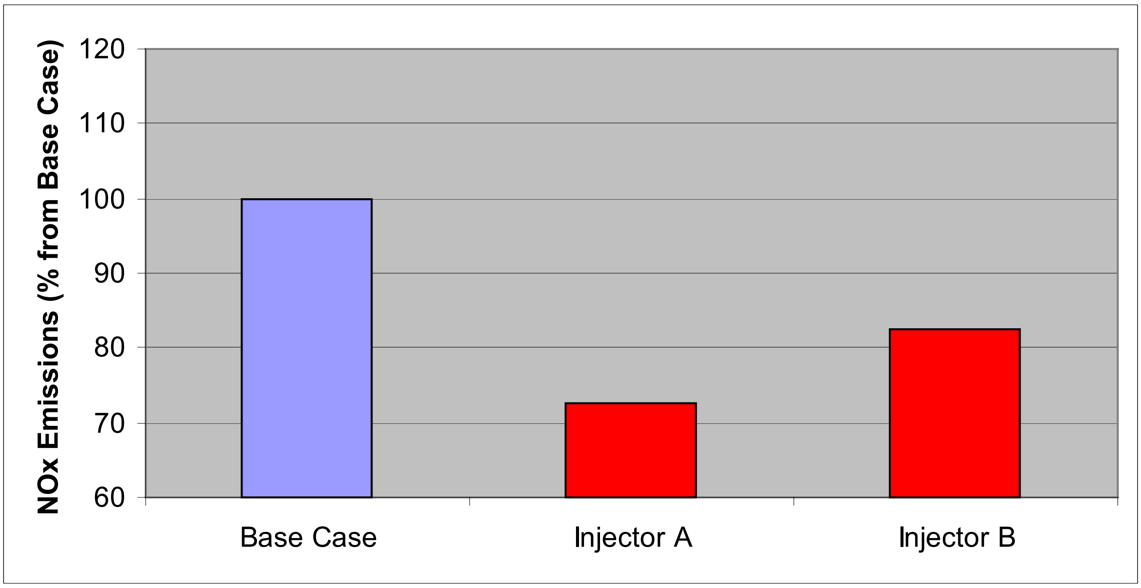

Figure 7. NO_x emissions results using various injection technologies at the tertiary oxidant level.

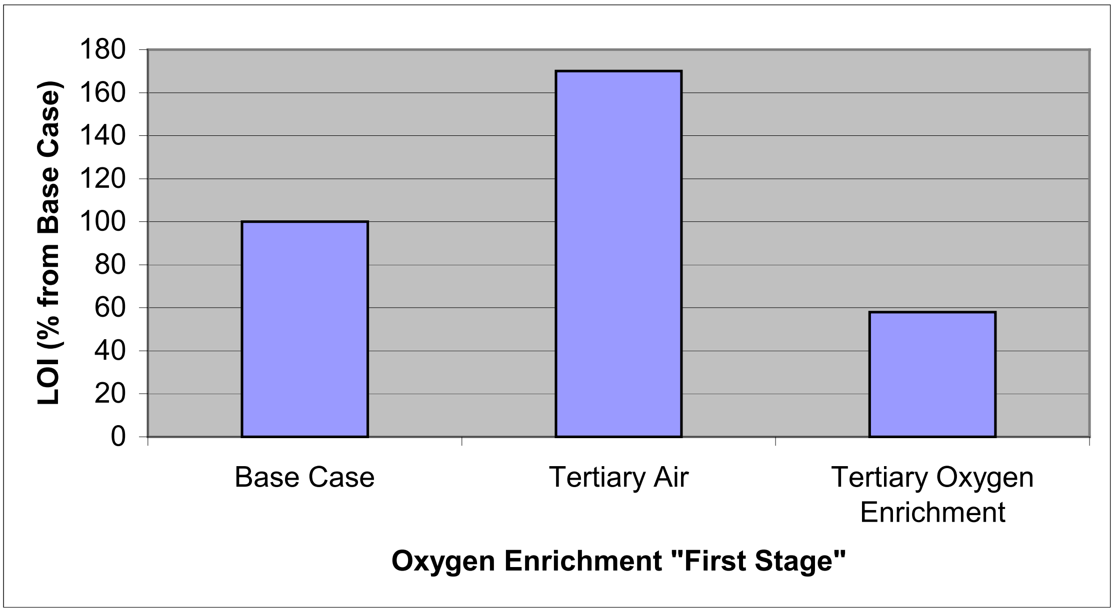

Figure 8. LOI results for the base case, tertiary air operation, and tertiary oxygen enrichment case, respectively.

The implication of these results is straightforward: the use of oxygen enrichment enhances the overall combustion process of pulverized coal in a boiler by reducing the NO_x levels quite significantly, and also by increasing the overall combustion efficiency. One conclusion emphasizes the fact that the concrete means for oxygen injection plays an important role. This knowledge is key in the process efficiency. It is noted that throughout the oxygen enrichment tests, the boiler operation has been extremely steady and safe, and oxygen injection has added flexibility in the combustion system, as the flow of oxygen can be easily controlled, unlike the air operation. It is also noted that during the oxygen enrichment tests, the temperature of the flue gas at the end of the combustion chamber, while it increased slightly due to improved efficiency and the reduction of nitrogen to quench the flue gas, did not seem to significantly alter the ratio between the radiative and convective heat transfer in the boiler. This fact is explained by the very small amount of oxygen introduced in the system, compared to the overall amount of oxidant. Future work will further optimize the impact of oxygen on the boiler operation, in order to achieve the best results with the minimum amount of oxygen, and therefore to further enhance the economics of the process. At the same time, it is necessary to develop new, advanced boilers, tailored for oxy-combustion, particularly for full oxy-fired boilers, but also for low-oxygen enrichment. Previous work (Horbaniuc *et al.* 2001) shows there is a great potential for high-efficiency, low-investment boilers using oxy-firing.

The preliminary economics of the process show that the impact of oxygen enrichment can be significant. Thus, the decrease in NOx and in unburnt fuel, enhanced ash quality and the potential to increase production result in an economical impact in excess of $200/ton oxygen used, making the use of oxygen highly attractive. A more detailed economical analysis is the focus of a future work.

CONCLUSIONS

This paper presents aspects related to the low oxygen enrichment technologies in pulverized coal fired boilers. The work described here is the result of a collaboration between AL, B&W, ILGS and ICCI, and includes results of tests performed on the 1.5 MW (5MMBTU/hr) B&W pilot boiler, using Illinois coal.

It is concluded that the use of small amounts of oxygen in a utility boiler has several advantages:

- Reduced NO_x emissions. The result is very important in the development of new, efficient, low-NO_x combustion systems.
- Increased combustion efficiency – thus, the unburnt coal in the ash has been reduced dramatically when using oxygen. This is a particularly important factor in the industrial operation, as low-C ash can be valorized by the utility company, instead of being landfilled and thus constituting an expense.
- Increased production – while it has not been demonstrated during the experimental work, oxygen enrichment constitutes a well-demonstrated means to increase the heat input in a combustion process.
- Increased process flexibility – the control of the oxygen flow is done very efficiently and fast, ensuring a stable operation, even in a dynamic mode.

Another key result from the experimental work indicates that the actual means to introduce oxygen in the system has an important impact on the process. Knowledge of the process, and also having the right hardware is very important in optimizing the process.

Oxygen enrichment has been proven as an effective means to control emissions and to enhance the combustion process. Future work will further optimize the oxygen enrichment techniques, in order to maximize the impact of oxygen in the boiler operation.

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