DILUTED OXYGEN COMBUSTION TO IMPROVE ENERGY EFFICIENCY IN STEEL MILLS[1]

Pedro Zagury[2]
Ritesh Kumar Nath[3]
Abílio Tasca[4]
Izaias Marques[5]
William Kobayashi[6]

Abstract

With increasing energy conservatism and pending CO2 legislation, steelmakers are striving towards fuel savings, energy efficiency improvements and the use of alternate fuels. Oxy-fuel technologies offer an economically feasible solution to meet these objectives. Compared to air-fired combustion systems, oxy-fuel technology can deliver up to 80% reduction in flue gas volumes, up to 50% fuel savings, up to 90% reduction in NOx emissions and the ability to substitute fuels. The specific benefits for each case are a function of several variables that are discussed in the paper. In addition, the paper describes how Praxair's Dilute Oxygen Combustion (DOC) technology overcomes all the classical concerns of oxy-fuel systems to offer an ideal oxy-fuel solution.

Key words: Oxygen; Combustion; Energy; Steel.

---

[1] *Technical contribution to 34º Seminário de Balanços Energéticos Globais e Utilidades e 28º Encontro de Produtores e Consumidores de Gases Industriais, 2013 August 28th to 30th, Vitória, ES, Brazil.*

[2] *Metallurgical Engineer. Technology and applications Manager da White Martins Gases Industriais Ltda. Rio de Janeiro, RJ, Brazil.*

[3] *Metallurgical Engineer. General Manager Steel and Combustion da Praxair India Private Limited. Bangalore, KA, India.*

[4] *Mechanical Engineer. Applications Development Manager da White Martins Gases Industriais Ltda. São Paulo, SP, Brazil.*

[5] *Electrical Engineer. Global Applications Equipment Technology Manager da White Martins Gases Industriais Ltda. Rio de Janeiro, RJ, Brazil.*

[6] *Metallurgical Engineer. Director Business Development da Praxair Asia Inc. Shangai, China.*

1 INTRODUCTION

Steelmakers are routinely challenged with rising energy costs and stricter emission standards. As a result, energy and emission footprints are under constant examination and review. Leading steelmakers are actively setting goals to reduce the energy intensity and CO_2 emissions from their processing routes, even though legislation is still pending in most countries.

Application technologies geared towards effective use of industrial gases can help steelmakers meet their increasing performance challenges, in the near term, without requiring relatively drastic changes to the processing routes. Conceptually, there are two broad categories of benefits that oxy-fuel technologies can bring to iron and steelmaking operations:

1) Improved Process Heating
2) Improved Combustion for burning and gasification

The requirements for these two categories can be envisaged at the opposite end of a "combustion spectrum", as depicted in Figure 1. Process heating at the left end of the spectrum requires dilute and uniform flames, while on the other end, burning and gasification requires intense, concentrated hot flames. Dilute flames are required for applications such as steel reheating or ladle preheating, while concentrated hot flames are typically required for rapid combustion of a variety of solid or liquid fuels. In the latter case, oxygen assisted combustion enables one to burn low heating value fuels or fuels that are poorly combusted in air. Over the years, Praxair has developed patented oxy-fuel technologies that cover this entire spectrum and can provide a well suited, tailored solution for any specific requirement.(1,2) Dilute Oxygen Combustion (DOC) is the predominant technology for the left end of the spectrum, while Hot Oxygen Technology is a specific technology for the right end of the spectrum. These will be described in more detail below.

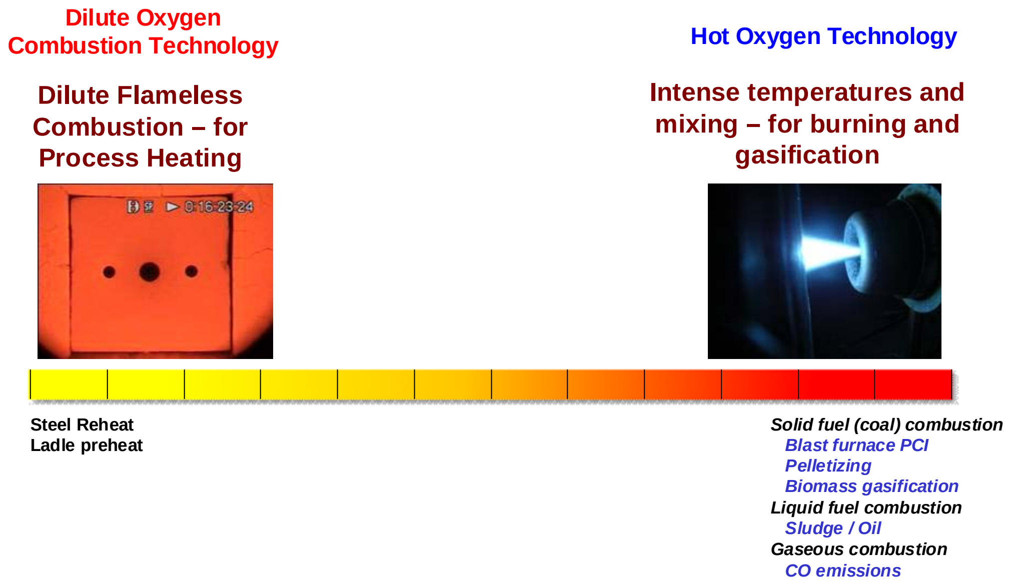

Figure 1: The oxy-fuel combustion spectrum and Praxair's applicable technologies.

2 PROCESS HEATING

For a process heating furnace such as a reheat furnace, oxy-fuel combustion reduces or eliminates nitrogen in the combustion air and substantially reduces the amount of waste heat carried out with the flue gas, compared to an air fired burner system. This reduction of the nitrogen ballast results in fuel savings and a reduction in flue gas volume for the same level of net available energy to the process. For a furnace using ambient air, the fuel savings can be up to 60% and the flue gas reduction is ~ 85%, as shown in Figure 2,(1,3) resulting into an optimally sized flue gas handling system at a substantially reduced cost, if addressed at a greenfield stage.

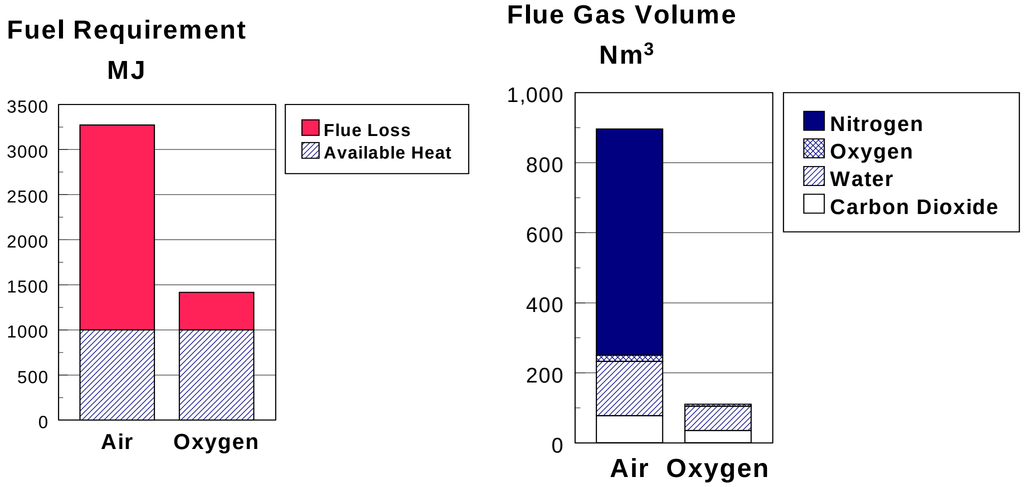

Figure 2: Comparison of fuel requirement and offgas volume for air-fuel vs oxy-fuel systems to deliver 1GJ of available heat to the process, assuming methane fuel, air at 21°C and flue gas at 1150°C.

If the baseline air-fired system uses preheated air with a recuperator or regenerator system, the degree of fuel savings decreases with the level of preheat, as shown in Figure 3.

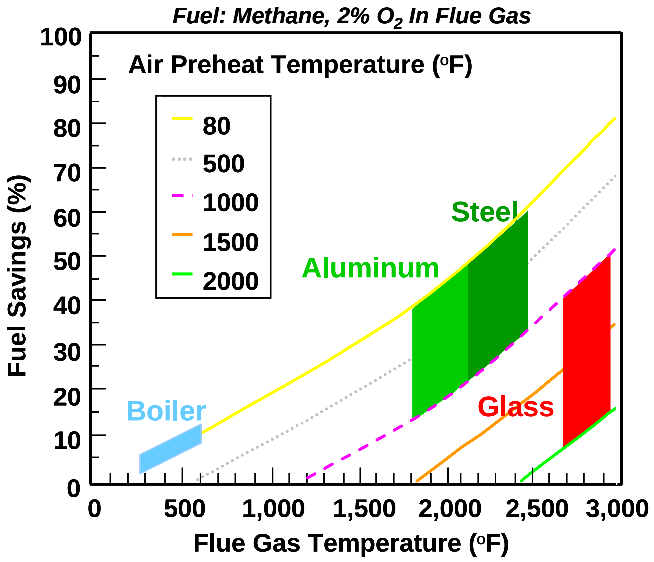

Figure 3: Oxy-fuel savings as a function of flue gas temperature and air preheat temperature.

- *Productivity*: One additional benefit of oxygen is the ability to boost furnace productivity, if required, without expensive capital outlays. Traditionally, productivity improvement (normally about 10% – 20%) is the "easiest" benefit that can be delivered by oxy-fuel technologies for a wide variety of furnaces and conditions.

- *Traditional Concerns with Oxy-fuel Systems*

Simple enrichment of air with oxygen or direct replacement of air with oxygen in a burner can produce very intense, high-temperature flames that have, at times, led to concern for temperature uniformity during oxy-fuel combustion heating. In some cases, the high-intensity oxy-fuel flames were considered damaging to the process and to the furnace refractory. Some of these concerns are summarized in Table 1 below. In reality, all of these concerns can be addressed with the appropriate technology, such as Praxair's Dilute Oxygen Combustion (DOC) technology discussed below.

Table 1: Traditional concerns of oxy-fuel usage for process heating

MYTH	REALITY
Oxy-fuel burners have high flame temperatures that will damage a furnace or product; increase NOx.	Oxy-fuel flame temperature can be made to match air-fired burners using DOC* principle, with lowest NOx.
The best way to use oxygen is to enrich combustion air.	Many injection strategies are available to maximize the benefits of oxygen.
Oxygen is too expensive.	Economic benefits from oxygen can significantly outweigh oxygen costs.

2.1 Praxair's Dilute Oxygen Combustion (DOC) Technology

Praxair has developed and patented low flame temperature oxy-fuel burners that can be used in high temperature industrial furnaces.(3,4) In Dilute Oxygen Combustion, the basic concept is separate the oxygen and fuel injection, so that the oxygen is injected into the furnace through a nozzle that is separated from the associated fuel jet. This allows the fuel to mix with a hot, dilute oxidant containing 2% to 10% oxygen to produce a low peak flame temperature "reaction zone", as shown in Figure 4. A minimum furnace temperature of 760°C (1,400°F) is typically preferred. This mixing and dilution produces a thermally uniform heat release with low peak flame temperatures just above the furnace temperature, resulting in low NOx (0.01-0.03 lbs/MM BTU or 5-15 kg/MJ) and more uniform temperature distribution throughout the furnace.

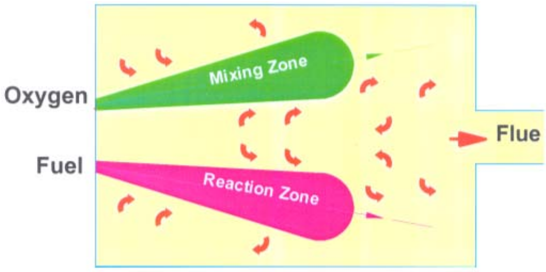

Figure 4: Schematic illustrating the Dilute Oxygen Combustion (DOC) concept.

Fuel and oxygen are injected separately at high velocity to create rapid dilution and diffuse "flameless" combustion.

DOC technology has been implemented on over 150 furnaces across a variety of industries globally. Three examples covered below in brief are continuous steel reheating, batch reheating and ladle preheating.

3 COMBUSTION AND GASIFICATION

3.1 Praxair's Hot Oxygen Technology

Hot Oxygen Technology(5,6) is a method of creating a high temperature, high momentum oxygen stream which is ideally suited for combustion applications requiring intense mixing. The combustion of a pulverized coal stream in the tuyere of a blast furnace is one example.

Hot Oxygen technology uses Praxair's patented thermal nozzle (Figure 5), in which a small amount of fuel is injected into an oxygen stream and fully combusted to heat up the oxygen jet. In this manner, a high temperature oxygen jet (up to 1,650°C / 3,000°F) is advantageously generated at the point of use, and directed through the exit nozzle into the customer's process. The high temperature raises the injection (sonic) velocity of the gas more than 150%. Table 2 shows typical hot oxygen jet chemistry.

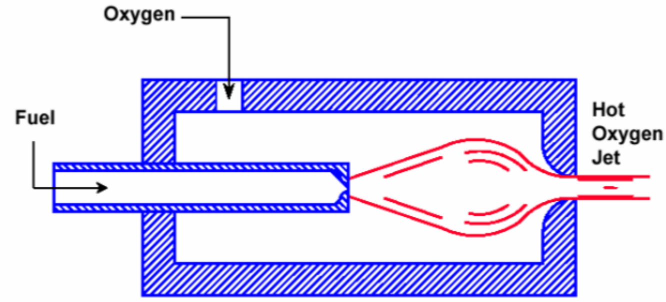

Figure 5: Schematic of Praxair's patented thermal nozzle to produce a hot oxygen jet.

Table 2: Hot oxygen jet conditions for two selected hot oxygen temperatures

Hot Oxygen Temperature	1370°C	1650°C
Reactants		
Oxygen, m³	100	100
Natural gas, m³	6.4	8.2
Products		
Total volume, m³	106.4	108.3
Oxygen, %	81.9	77.1
Carbon dioxide, %	6.0	7.6
Water vapor, %	12.1	15.0
Sonic velocity, m/s	745	803

Some of the potential applications for hot oxygen technology include:

- Solid fuel (coal) combustion
    - Blast furnace PCI (discussed in Section 5.4)
    - Pelletizing
    - Biomass gasification
- Liquid fuel combustion
    - Sludge
- Gaseous combustion
    - CO emissions

4 FUEL SUBSTITUTION

Steel plants usually have an abundance of low heating value fuels such as blast furnace gas (BFG). However its usage is limited by the fact that the combustion of BFG with air results in a low flame temperature, below the requirement of many steelmaking processes. Often, BFG may be flared for this reason. On the other hand, it is common practice to “sweeten” the BFG with a higher heating value fuel such as natural gas (NG) or coke oven gas (COG) to create a fuel blend, increase its heating value and therefore its flame temperature with air, as shown in Figure 6.

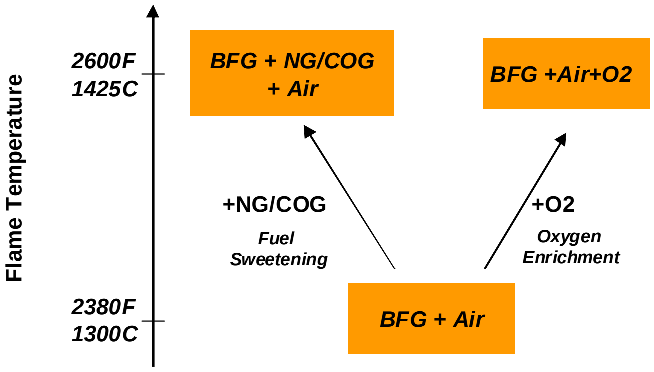

Figure 6: Schematic illustrating the concept of oxygen enrichment to raise flame temperature as an alternative to sweetening with higher value fuels.

A more economical alternative to fuel sweetening can be oxygen enrichment; i.e. the addition of medium to high purity oxygen to the combustion air. This approach is used in Praxair’s Stove Oxygen Enrichment (SOE) technology for blast furnace stoves, is described in Section 5.2.

Ultimately, a BFG-oxygen system can completely substitute a NG-air system. NG-air and BFG-oxygen produce virtually identical volumes and temperatures of combusted gas, Figure 7. In this manner, the selection of NG-air or BFG-oxygen is transparent to the process itself.(7)

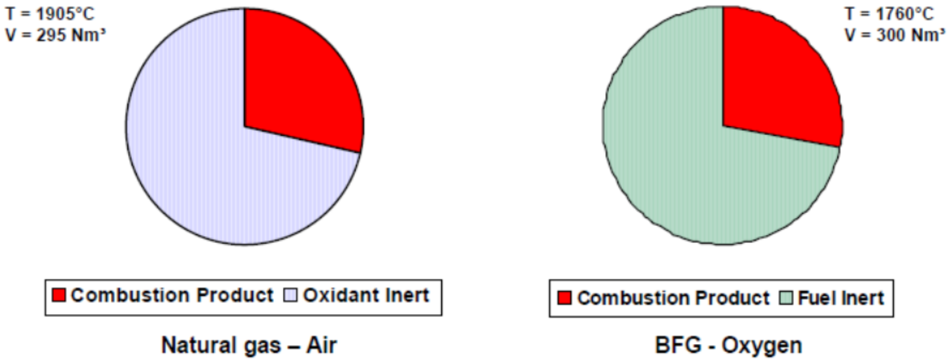

Figure 7: Comparison of combustion products, flame temperatures and volumes for NG-Air and BFG-Oxygen systems, each producing 1 MMBtu (1.055 GJ) of heat.

5 EXAMPLES AND RESULTS

5.1 Steel Reheating

Two strategies can be employed to reduce overall energy and emissions from reheat furnaces. The first utilizes a conversion of one or more zones of the furnace from air-fuel to oxy-fuel. This approach can be used without any adjustments to the fuel blend consumed within the furnace. Praxair has demonstrated fuel savings of 20%-45% for furnace zones that were converted from air-based combustion systems to oxygen-based combustion systems and annual cost savings of \$200,000 to \$450,000 per furnace.(8,9) Conversion of the zones closest to the charge end of the furnace typically result in the largest fuel savings on a per ton of steel basis as these are the largest zones in the furnace. For furnaces that do not require significant quantities of supplemental fuel, this approach will free up by-product fuel for use in other parts of the plant. These fuels can ultimately displace the use of purchased fuel and thereby reduce the overall CO_2 emissions from the entire plant.

The installation of Praxair's DOC technology on an 84" pusher type continuous reheat furnace is shown in Figure 8 below. The oxy-fuel lances were retrofitted within the existing burners so that no refractory work was required on the furnace. The 153 GJ/hr (145 MM BTU/hr) oxy-fuel system in the primary zone of the reheat furnace achieved fuel savings of 0.27 GJ/ton of steel and consumed 0.026 tons of oxygen/ton of steel, for a net savings of approximately 10 GJ/ton of oxygen.

Figure 8: Reheat furnace burners (a) without DOC lances and (b) with DOC fuel and oxygen lances installed.

The alternative approach for oxy-fuel application in a reheat furnace is to adjust the fuel blend used in the furnace. As with blast furnace stoves, BFG-oxygen burners can mimic NG-air or COG-air burners in reheat furnaces. Combustion with oxygen allows a higher percentage of BFG in the fuel mix, stretching the available COG supply. Due to the much lower heating valve of BFG, the fuel supply system will need to be modified to accommodate an order of magnitude higher flow – see Table 3.

Table 3: Comparison of NG-air, COG-air, and BFG-oxygen Combustion

	NG-Air	COG-Air	BFG-Oxygen
Fuel high heating value, MJ/Nm³	40	20	3.6
Btu/scf	1000	500	90
Fuel required, Nm³/GJ	25	50	278
scf/MMBtu	1000	2000	11,110
Air / Oxygen required,* Nm³/GJ	253	230	43
scf/MMBtu	10,105	9,213	1702

** for 1% oxygen in flue gas*

5.2 Batch Reheating

In one of a recent installation of DOC technology on a new “Box” type forge reheat furnace,(10) the critical aspect was the achievement of temperature uniformity better than ±13°C (±25°F), as measured by a temperature survey conducted per AMS-2750D standard. The actual results with DOC technology demonstrated results within ±11°C (±20°F) for all 14 thermocouples that were employed for the measurement.

Table 4: Results of temperature uniformity measurements in a forge reheat furnace

Setpoint	Avg Temp °F	Max Temp °F (+)	Min Temp °F (-)
843°C / 1550°F	1552.1	9	13
1037°C / 1900°F	1901.3	10	14
1260°C / 2300°F	2299.4	11	12

The corresponding NOx results were as follows:

Table 5: Results of NOx measurements in a forge reheat furnace

Firing Rate %	CO	NO	CO2	%O2	NOx (lb/mmBtu)
100	11	13	84	0.9	0.0019
90	18	15	83	1.2	0.0022
80	13	18	83	1.1	0.0026
70	16	14	82	1.1	0.0021
60	15	12	81	1.2	0.0018
50	14	14	80	1.3	0.0021
40	13	9	79	1.4	0.0014
30	13	14	77	1.4	0.0022
20	11	5	61	1.8	0.0010
10	11	5	60	2.1	0.0010
Average	14	12	77	1.4	0.0018

DOC Technology was recently installed in a soaking pit for specialty steel ingot processing in India. The driver for changeover to DOC was was reduction in specific Furnace Oil consumption and increase in Heating Rate. The results achieved are as follows:

Table 6: Results of fuel savings in a soaking pit furnace

[redacted]

5.3 Continuous Reheat Furnace

Most recently implementation of DOC Technology goal was to minimize fuel oil consumption by replacing it with oxy-BFG and managing the maximum flue gas flow rate due to the limitation in the existing system. Fuel oil consumption could be zeroed if there was no fuel gas system limitation. The results were achieved with DOC Hybrid configuration. Praxair DOC Hybrid installation is easy to be conducted and don't require long furnace shut-down time like in cases of full burner replacement.

Table 7: Results of fuel savings in a continuous reheat furnace

[redacted]

5.4 Blast Furnace Stove Oxygen Enrichment

Stove Oxygen Enrichment (SOE) is a method to add high-purity oxygen to the stove combustion air to eliminate the use of sweetening high value fuels, as discussed in Section 4. It is used commercially in North America, South America, and Asia. Table 6 shows the results of commercial operation with SOE on three blast furnaces, demonstrating how oxygen can effectively lower or eliminate the use of higher heating value fuels depending on the ironmaker's overall strategy.(2,7,11) Use of natural gas was completely eliminated at the two mills in the USA and coke oven gas usage was reduced by about 36% at the mill in Asia. In addition, a higher concentration of CO_2 in the SOE combustion gas provides greater radiative heat transfer in the dome, and thereby lowers the dome temperature and fuel consumption.

Table 8: Performance data for Stove Oxygen Enrichment

	Furnace 1 (USA)	Furnace 2 (USA)	Furnace 3 (Asia)
Furnace production rate, t/d	10,000	3600	1900
Conventional operation			
Natural gas, Nm³/t	15.8	11.2	--
Coke oven gas, Nm³/t	--	--	10.4
SOE			
Oxygen, Nm³/t	23.8	28.8	4.4
Additional BF gas, Nm³/t	164.7	147.1	23.0
Natural gas, Nm³/t	0	0	--
Coke oven gas, Nm³/t	--	--	6.7
Saving of high value fuel	100%	100%	36%

The amount of oxygen required for SOE depends largely on the quality (heating value, moisture content, etc.) of the blast furnace gas. Using a dome temperature controller to adjust oxygen enrichment throughout the heating cycle has been shown to significantly lower oxygen requirement.

5.5 Ladle Preheating

Although ladle preheating consumes a relatively small portion of the overall energy budget of a steelmaking plant, it is an inefficient energy consumer and can benefit from improvements in combustion technology. Furthermore, poor ladle preheating can have a large effect on the energy efficiency of the largest energy consumers within the steelmaking shop such as the electric arc furnace, LD converter and/or the ladle metallurgy furnace. Since most modern steelmaking ladles need to be preheated above 1150°C (2100°F), greater than 60% of the energy is exhausted to the stack if ambient air-fired burners are used. Under these conditions, Praxair's Dilute Oxygen Combustion system provides a means of cutting energy consumption by greater than 50%, while simultaneously lowering carbon emissions and NOx emissions. Figure 9 shows a typical ladle preheater installation, and Table 9 summarizes the results achieved at selected customers.(12)


(a) (b)

Figure 9: Typical DOC ladle preheater installation showing (a) the piping connections on the cold face and (b) the hot face of the burner block.

Table 9: Results of oxy-fuel ladle preheating at Praxair customers

	Benefit				
Customer	**Fuel Consumption**	**Tap Temperature**	**Ladle Life**	**Cold Ladles**	**Aborted casts**
A	50%	No Change	Improved	Improved	Reduced
B	Not documented			Improved	Reduced
C	50%	40°F decrease	No change	No change	No change
D	50%	11°F decrease	No change	No change	No change
E	51%	No Change	No change	No change	No change
F	50%	No Change	No change	No change	No change

6 CONCLUSION

Many oxy-fuel technologies are available to help steelmakers reduce their energy and emission footprints. These technologies can be deployed in the near term, without requiring significant capital costs and with relatively minor changes to the current processes.

Dilute oxygen combustion is a fundamental oxy-fuel technology that has been implemented on a variety of furnaces across many industries. It overcomes all the classical concerns of oxy-fuel systems to offer an ideal oxy-fuel solution. In steelmaking, DOC has been used successfully for steel reheating and ladle preheating. Fuel substitution applications such as Stove Oxygen Enrichment (SOE) are becoming widely adopted worldwide, allowing higher value fuel gases like COG and natural gas to be conserved or used in higher value applications. In a blast furnace, the tuyere injection of hot oxygen can significantly improve the ignition and burnout of tuyere injected fuel, helping to raise fuel injection levels and minimize coke consumption.

Over the years, Praxair has developed the above patented oxy-fuel technologies that cover this entire combustion spectrum and can provide a well suited, tailored solution for any specific requirement.

REFERENCES

1 L.M.Farrell, T. Pavlack, L. Rich; "Operational and Environmental benefits of Oxy-Fuel Combustion in the Steel Industry", 12th PTD Conference, Iron and Steel Society, Warrendale, PA, 1993, p.185-199

2 S.K.Warty, et al.; "Application Technologies for Blast Furnaces", SteelTech Proceedings, Kolkata, India, 2010

3 M.F. Riley, H. Kobayashi, A.C.Deneys, "Praxair's Dilute Oxygen Combustion Technology for Pyrometallurgical Applications", Journal of Metals, May 2001, p.21

4 US Patents 5,076,779; 5,266,025; 5,387,100; 5,449,286; 5,601,425; 5,755,818; 5,924,858; 6,007,326; 6,394,790

5 M.F. Riley, T.J. Strayer, and Y. Zhao, "Effect of Direct Oxygen Injection on Combustion of Injected Coal", Proc. 2nd International. Congress on the Science and Technology of Ironmaking, Iron & Steel Society, Warrendale PA USA, 1998, pp. 683-688.

6 M.F. Riley, “Hot Oxygen Injection into the Blast Furnace” U.S. Dept. of Energy report DOE/ID/13554/9718, October 21, 2002, <http://www.osti.gov/bridge/servlets/purl/805785-IPYrJ2/>

7 M.F.Riley, L. Rosen, R. Drnevich; Mitigating CO2 Emissions in the Steel Industry: A Regional Approach to a Global Need; Proceedings AISTech 2009, AIST, Warrendale PA, 2009, vol. 1, pp. 89-101

8 F. Erfurth, et al., “Fuel Savings for Slab Reheating Furnaces Through Oxyfuel Combustion”, AISTech 2006 Conference Proceedings, AIST, Warrendale PA, 2007, pp. 1071-1075.

9 E. Black, et al., “Installation of a 145 MMBtu/hr Oxyfuel Firing System on the #2 Reheat Furnace at ArcelorMittal’s 84" Hot Strip Mill”; AISTech 2009 Proceedings - Volume II, AIST, Warrendale PA

10 L. Cates “Improved Temperature Uniformity in Batch Reheat Furnaces with Praxair’s Dilute Oxygen Combustion (DOC) technology”, in AIST conference proceedings “The Iron and Steel Technology Conference and Exposition AISTech 2010” May 3-6, 2010.

11 J. Bobeck, et al., “Stove Oxygen Enrichment at Arcelor Mittal’s #7 Blast Furnace”, AISTech 2008 Proceedings, AIST, Warrendale PA

12 J. Kelly, et al. “Oxygen Enhanced Ladle Preheating Systems: Improved Tap-to-Tap Cycle Time and Operating Cost Reductions”, Proceedings AISTech 2010, AIST, Warrendale PA, 2010.