Bethlehem Steel's Evaluation of a Low NO_x Oxy-Fuel Burner[1]

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ABSTRACT

Bethlehem Steel has been proactive in its history of energy efficiency, and one aspect of that activity is partnering with others. Under the U.S. Department of Energy's NICE[3] (National Industrial Competitiveness through Energy, Environment, and Economics) Program, burners at a batch furnace in the 160" plate mill of Bethlehem's Burns Harbor Division were converted to low-NO_x oxy-fuel burners based on Praxair® Dilute Oxygen Combustion technology. Four burners with a total firing capacity of 24 MMBtu/hr were installed and operated on coke oven gas. A fuel reduction of 60% from baseline air burner operation was achieved. Slab heating uniformity was satisfactory. NO_x emissions were reduced by 60% from the baseline. This NO_x reduction was achieved with the existing furnace structure that allows air infiltration through the furnace doors. Particulate emissions were 94 percent lower. Increased deterioration of the burner block was noted. Net furnace operating costs were approximately 40% below baseline costs. Operating cost savings total $200,000 annually, based on 1998 fuel costs, or $450,000 annually, based on fuel costs for July-December 2000.

Acknowledgements

This project was conducted under Grant Agreement SW-012 from the State of Indiana through the Indiana Department of Commerce, Energy Policy Division and the NICE[3] (National Industrial Competitiveness through Energy, Environment and Economics) Program of the U.S. Department of Energy, Office of Industrial Technologies. Sincere appreciation is extended to the U.S. Department of Energy, Office of Industrial Technologies and the Indiana Department of Commerce, Energy Policy Division for their financial and administrative support in partnering with Bethlehem Steel and Praxair to demonstrate and evaluate these low-NO_x oxy-fuel burners.

This project involved many challenges, including the development of coke oven gas burner components and the design, installation, debugging, operation, monitoring, and evaluation of the new burner and control equipment. Special thanks are offered to the Bethlehem Steel and Praxair employees who worked through the problems and difficulties encountered, particularly during installation and debugging. Thanks are also extended to the experts at Kvaerner Songer, Inc., North American Manufacturing Co. and Advanced Combustion Inc. who contributed to the successful completion of this project.

[1] Abbreviated version.

Project Background

Bethlehem Steel Corporation and the other companies of the steel industry have practiced energy conservation throughout their history. Bethlehem's Energy Conservation Policy is

> *"to use energy in the most cost-effective and environmentally sound manner and to promote and apply best available energy use technology".*

Steelmaking, including the process of reheating steel prior to hot rolling, is very energy-intensive. Currently, regenerative or recuperative methods are used to conserve energy by using the heat content of the waste gases to preheat combustion air. Oxygen enrichment of the combustion air has been attempted with conventional burners, resulting in increased NO_x emissions and higher flame temperatures with little productivity increase or fuel reduction. However, oxy-fuel burners based on Praxair® Dilute Oxygen Combustion (DOC) technology using 100% oxygen have shown benefits in energy reduction, operating costs, and NO_x reduction in laboratory tests and in commercial application in other industries.

Over its long history of energy and environmental consciousness and stewardship, Bethlehem Steel has found that partnering with others is an important aspect of energy conservation activities. Partnering improves cost effectiveness, reduces risk, improves competitiveness, and improves the environment. The "Industries of the Future" initiatives of the U.S. Department of Energy, Office of Industrial Technologies, offer many partnership opportunities. Based on the reported results of DOC burners and these opportunities to partner with others, Bethlehem hosted a commercial demonstration of this low-NO_x oxy-fuel burner at the 160" plate mill in Burns Harbor, IN. Bethlehem partnered with Praxair, Inc. and the State of Indiana Department of Commerce in this project, carried out as part of the NICE^3 (National Industrial Competitiveness through Energy, Environment, and Economics) program, an innovative cost-sharing program for state and industry partnerships that demonstrate advances in energy and environmental efficiencies.

Praxair® Dilute Oxygen Combustion (DOC) Technology

Controlling the generation of nitrogen oxides (NO_x) in industrial combustion processes is essential to mitigating acid rain, ground level ozone, and photochemical smog.[1,2] The primary mechanism for NO_x formation is the Zeldovich, or "thermal NO_x" mechanism, which is very sensitive to peak flame temperature, nitrogen level, and excess oxygen level.[1]

Burners based on Dilute Oxygen Combustion (DOC) technology, patented by Praxair, Inc., provide very low levels of NO_x by controlling each of these sensitive parameters.[3,4] DOC burners inject fuel and oxygen *separately* into a furnace as high-velocity jets. With DOC technology fuel and oxygen do not react directly. Instead, the high-velocity oxygen jet mixes rapidly into the furnace gas, and the fuel jet entrains and reacts with this high-temperature, dilute-oxygen furnace gas. This dilution leads to low peak flame temperatures. In addition, since DOC burners use oxygen rather than air for combustion, there is no nitrogen added to the combustion process. Lastly, the flow controls employed with oxy-fuel systems offer close control of excess oxygen. This combination of temperature control, nitrogen control, and excess oxygen control leads to very low NO_x generation by DOC burners.

DOC burners also offer the other operating benefits characteristic of oxy-fuel operation, including the potential for productivity improvement and fuel savings of 50% or more.[5] In addition, the rapid circulation of furnace gas and the diffuse DOC flame provide a very uniform heating pattern.

DOC burners provide stable combustion under most normal operating conditions. However, below autoignition temperature, DOC combustion may be unstable. Tests have shown that by providing a small annular flow of oxygen around the fuel jet, low-temperature stability is vastly improved while NO_x levels show only a modest increase. For furnaces that may operate below autoignition, or that have periods with significant ambient air infiltration, these stabilized DOC burners offer excellent potential for NO_x reduction. Based on the use cycle of the batch furnaces at the Burns Harbor 160" plate mill, stabilized DOC burners were used for this evaluation.

The demonstration was conducted with these goals:

- Demonstrate a 45% reduction in fuel rate and a net operating cost saving.
- Demonstrate a 70% reduction in NO_x generation.
- Maintain heating quality as demonstrated by furnace temperature uniformity, slab heating rate, and rolling mill performance.

Facility Description

The Burns Harbor Division of Bethlehem Steel Corporation operates a 160" carbon steel plate mill. The rolling mill has one 2-high stand and one 4-high reversing stand. Plate can be rolled from 3/16" to 1.5" thick, 36" to 150" wide, and 60" to 1512" long, at a production capacity of 1.14 million tons per year.[6] Two continuous reheat furnaces heat most of the product for routine production. Special items are heated in one of three in/out batch furnaces or one pusher batch furnace.

The No. 6 in/out batch furnace is a rectangular enclosure, 52' 3" long, 15' deep, and 6' 6" high. The furnace walls and roof are super plastic refractory; the end walls are 18" thick, the front and rear walls are 13½" thick, and the roof is 11½" thick. The floor is 22" thick firebrick. The front of the furnace has two charge doors, each 22' long, so that roughly 84 percent of the front face of the furnace can be opened.

Before conversion to oxy-fuel, each end wall was equipped with 4 coke oven gas-cold air burners having a nominal total firing rate of 50 MMBtu/hr. The burner locations were biased toward the front (door) side of the furnace. The burners at each end were controlled separately, creating a North zone (to the right facing the doors) and a South zone (to the left facing the doors). The furnace was equipped with a down-draft flue located in the center of the furnace hearth. There are three flue openings to the furnace, each 3' by 3' 8".

The No. 6 in/out batch furnace burns coke oven gas. Natural gas is available as a backup fuel when coke oven gas is unavailable. Although the coke oven gas used to fuel the furnace has a variable composition which depends on the cokemaking process, the hydrogen to carbon ratio is quite consistent.[7] This consistency simplifies the analysis of the furnace gas combustion products since it allows water vapor levels to be calculated from the carbon dioxide analysis.

Oxy-Fuel Equipment and Furnace Modifications

Stabilized DOC Burner

The eight existing air-fuel burners were replaced by four stabilized DOC burners. The burner consists of separate fuel and oxygen lances mounted in a 60% alumina refractory burner tile and fitted with a steel mounting plate to connect to the furnace shell. A second oxygen connection provides the stabilizing oxygen flow to an annular passage surrounding the fuel lance. Burners were placed in the second and fourth burner ports from the door on each side of the furnace. In anticipation of fuel reductions on the order of 50%, the burners were designed for a nominal firing capacity of 6 MMBtu/hr, or 24 MMBtu/hr for the entire furnace.

High-momentum fuel and oxygen jets are essential to producing low NOx levels with this burner. The momentum of the fuel and oxygen jets is regulated primarily by the bore diameter of a replaceable nozzle threaded into the discharge end of each lance.[7] Experimentation with the furnace showed that more heat was required from the burners near the furnace door, and eventually the larger fuel nozzles were inserted in these door-side burners to provide 7.2 MMBtu/hr from the door-side burners and 4.8 MMBtu/hr from the rear-side burners.

The burner tile also contained a passage for a pilot ignition / UV flame detector assembly. For a cold startup of the furnace (temperature < 1600°F), a premixed air-natural gas stream was supplied to the pilot system and ignited by a spark. This pilot flame was used to ignite the main fuel flow. The UV sensor verified the presence of a flame until the furnace reached 1600°F. Any loss of flame signal below this temperature resulted in a furnace shutdown.

Burner Operating Modes

The burner was operated in a different mode at very low furnace temperatures to ensure safe operation. To minimize any concerns about flame stability, all of the combustion oxygen was delivered through the stabilizing annulus at furnace temperatures below 1600°F. Once this temperature was achieved, the normal operation began, with the bulk of the oxygen flow being provided through the oxygen lance. For the tests reported here, the burners were operated with approximately 85% of the oxygen supplied through the oxygen lances.

Reheat Furnace Flue

The flue gas volume of an oxy-fuel system operating at 2400°F is one-ninth that of an air-fuel system.[5] This sharp drop in off-gas volume allows an oxy-fuel in/out furnace to be operated without a flue. In fact, to maintain correct furnace pressure and minimize air infiltration, the flue must be eliminated. All furnace emissions are then fugitive emissions. Accordingly, as part of the furnace conversion, the flue ports in the hearth were sealed off.

Baseline Data

Furnace operation with the existing air-fuel burners was monitored to give a baseline for comparison with the stabilized DOC burners.

Furnace Temperature

Eight type-S test thermocouples were placed in the furnace roof in a 2 x 4 grid. The output from these thermocouples and the control thermocouples, located in the center of each zone, was recorded by a digital data acquisition system. In general, the five thermocouples in each zone showed good agreement.

During baseline testing, the average reading from all 10 thermocouples was 2332.2°F. Figure 1 shows the deviation between the average reading from each thermocouple and this overall average. A small temperature gradient was observed, with higher temperatures seen near the doors and lower temperatures near the rear wall. The control thermocouples read close to the overall average temperature. The maximum and minimum readings differed by 119.4°F.

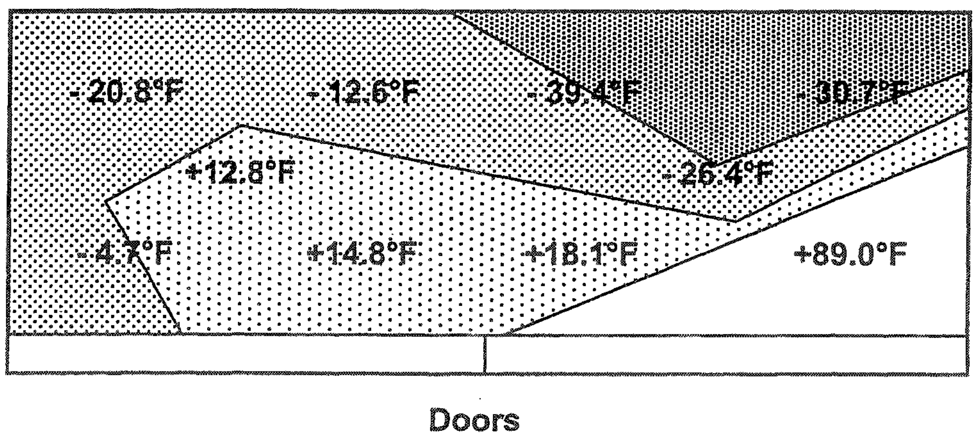

Figure 1. Deviation of Average Thermocouple Readings from Overall Average of 2332.2°F

Furnace Gas Analysis

Method. The furnace atmosphere was sampled from two sampling ports in the back wall of the furnace, one foot below the burner centerline and 20' from the end walls. These positions were selected to give samples that were representative of the furnace gas entering the flue. Since the flue was closed off when oxy-fuel burners were installed, this location provided consistent sampling sites for both baseline and oxy-fuel tests.

Sampling was done with a heated probe and sample line. The sample was filtered and dried before being distributed to a bank of analyzers. The sample was analyzed simultaneously for CO_2, CO, O_2, SO_2, and NO. The output from the analyzers was collected with a digital data acquisition system. The amount of water removed from each sample was calculated from the CO_2 and CO analysis and the average H_2 / C ratio of the fuel gas. The balance of the gas was assumed to be nitrogen.

Nitrogen oxide (NOx) generation. Furnace NO levels were converted to a mass of NO_2 generated per MMBtu of fully-combusted fuel gas. The level of NO_2 generated was primarily a function of furnace oxygen level, as shown in Figure 2. The variability of furnace oxygen level is caused by increases in air infiltration into the furnace at lower firing rates. Thus, the furnace oxygen level was essentially controlled by the furnace firing rate, and, as expected, NO_2 varies with firing rate as shown in Figure 3. At low firing rates, NO_2 generation increases sharply as furnace oxygen levels rise.

The standard method for measuring NOx calls for an analysis of 3 one-hour periods. Because of the variation in NOx throughout a heating cycle, the three test periods were selected to be representative of the total normal operation of the furnace. The selected periods corresponded to the last hour before reaching set point temperature, the first hour after reaching set point, and an hour during the soak (temperature equalization) period. This baseline NOx analysis is shown in Table I. The average NOx emission rate is 0.328 LB/MMBtu. With an average firing rate of 36.7 MMBtu/hr, NOx emissions equal 10.89 LB/hr.

Particulates

Three one-hour particulate emissions tests were performed according to 40 CFR 60 Methods 1-5. The average particulate emission rate was 3.70 LB/hr.

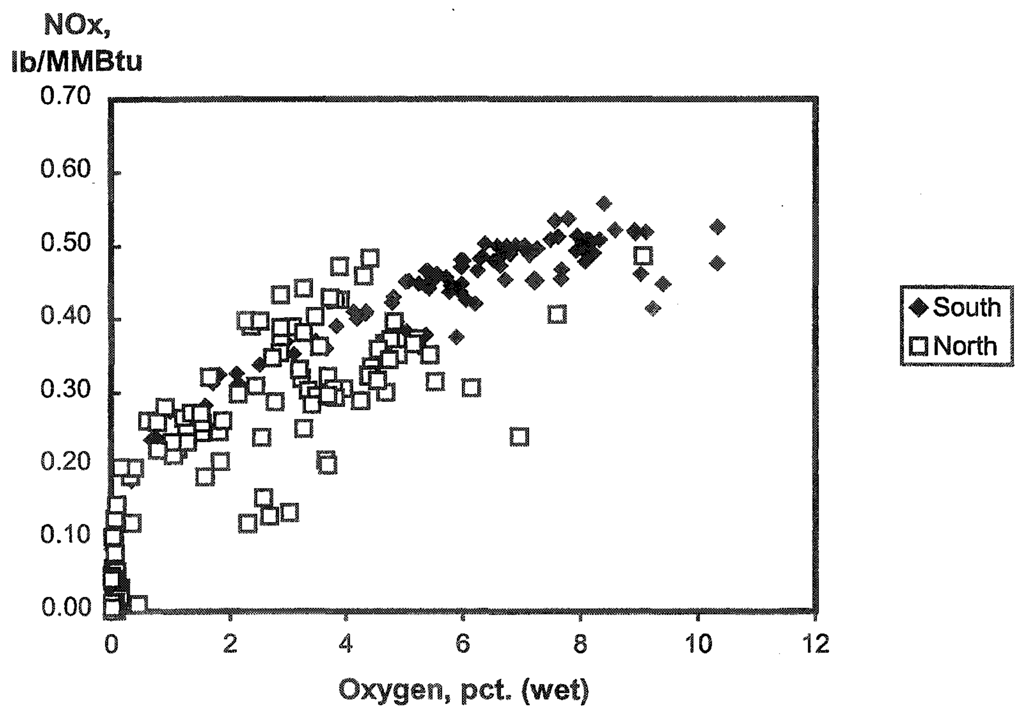

Figure 2. Furnace NOx as Function of Excess Oxygen Level for Baseline Tests

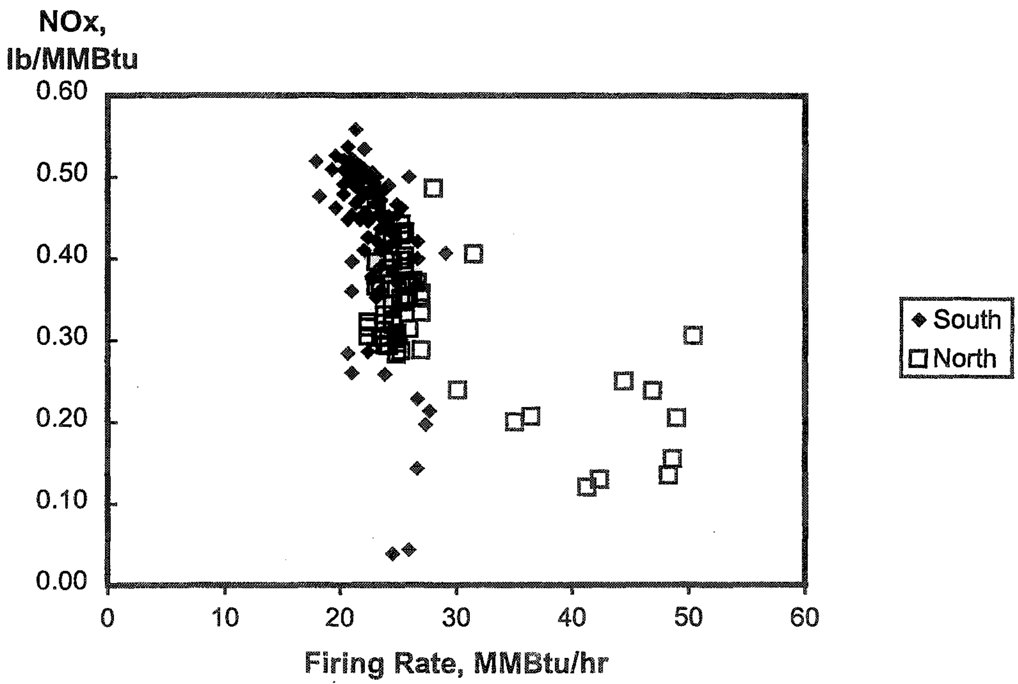

Figure 3. Furnace NOx as Function of Firing Rate for Baseline Tests

Table I. One-Hour Average Baseline NOx Measurements

	Before Setpoint	At Setpoint	Soak	Average
Average NOx, LB/MMBtu	0.223	0.288	0.472	0.328
Average Firing Rate, MMBtu/hr	48.2	39.9	22.1	36.7
Average NOx, LB/hr	10.75	11.49	10.43	10.89

Fuel Consumption and Productivity

The average fuel consumption and productivity for no. 6 furnace were calculated from monthly furnace performance reports. The average fuel consumption was 5.08 MMBtu/ton. On days when the furnace was firing, average production was 5.78 tons/hr. When tons were reported (i.e., excluding heat-up periods), the average firing rate was 32.0 MMBtu/hr.

There is some discrepancy between the fuel rate and firing rate calculated from monthly averages and those calculated from the 3 one-hour NOx test periods. The discrepancies can be reconciled by observing that in practice the furnace spends more that one hour out of three soaking the charge, that is, the three periods used in Table I tend to under-emphasize emissions during the soak period.

Low-NO_x Oxy-Fuel Test Data

Furnace Temperature

With the furnace converted to oxy-fuel firing and with each stabilized DOC burner fired at a nominal 6 MMBtu/hr capacity, the maximum and minimum readings differed by 299.2°F. In addition, the front-to-back temperature gradient observed in the baseline tests was replaced by a temperature peak near the longitudinal furnace axis. This means that the control thermocouples were now reading peak temperatures instead of average temperatures.

In an attempt to reproduce the baseline temperatures more closely, the fuel nozzles on the burners were changed to provide 7.2 MMBtu/hr capacity to the door-side burners and 4.8 MMBtu/hr capacity to the rear-side burners. With this arrangement, the five thermocouples in each zone show good agreement. Figure 4 shows the deviation from the overall average temperature for each thermocouple. The overall average temperature from the 10 thermocouples was 2275.9°F, and the maximum and minimum readings differed by 121.5°F. The peak temperatures still occur near the longitudinal furnace axis. However, since the uniformity of temperature is essentially the same as the baseline, by increasing the setpoint of the furnace by 50°F, similar heating quality can be achieved in the furnace.

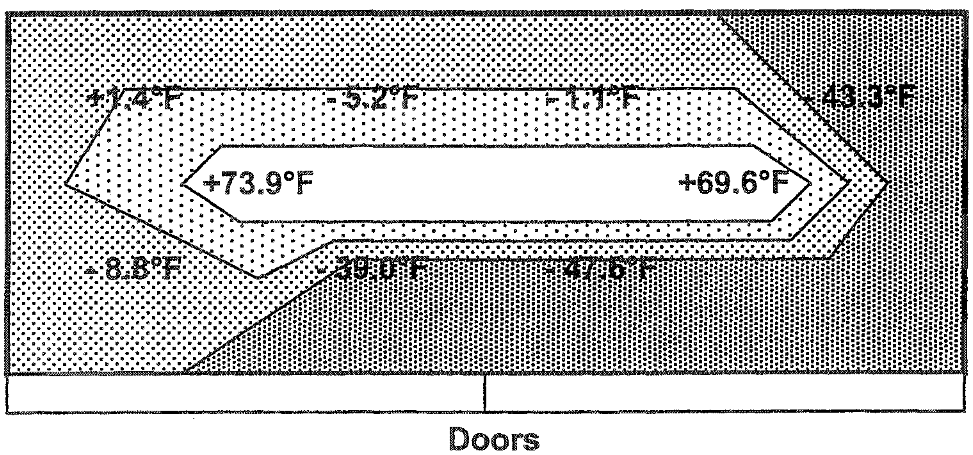

Figure 4. Deviation of Average Thermocouple Readings From Overall Average of 2275 F, with Burners Biased Toward Doors

Furnace Gas Analysis

Nitrogen Oxide (NOx) Generation. NOx again varied with firing rate as shown in Figure 5, apparently because of higher rates of ambient air infiltration at low firing rates. Although the oxygen to fuel ratio was reduced at low firing rates to control furnace oxygen level, the increase in furnace nitrogen levels led to higher rates of NOx generation.

Table II shows the NOx levels observed over 3 one-hour periods corresponding to periods analyzed for the baseline data. The average NOx generation rate is 0.283 LB/MMBtu, 13.7% lower than baseline. With an average firing rate of 18.8 MMBtu/hr., this NOx generation rate equals 4.38 LB/hr, 60% lower than baseline.

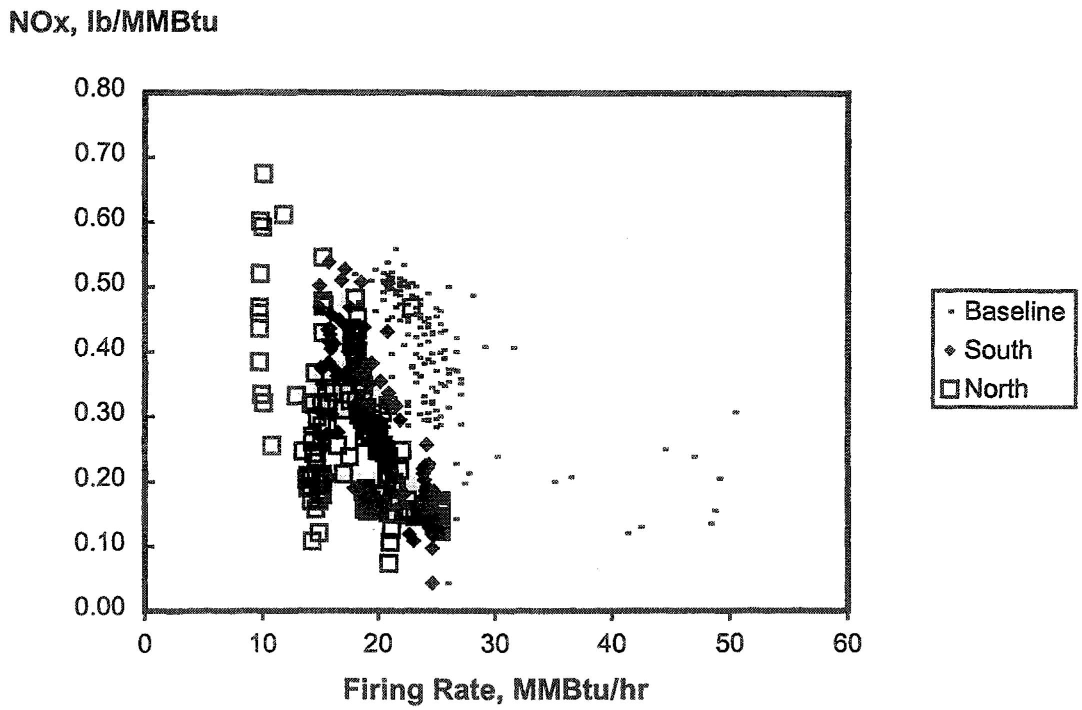

Figure 5. Furnace NOx as Function of Firing Rate for Oxy-Fuel Tests

Table II. One-Hour Oxy-Fuel Average NOx Measurements

	Before Setpoint	At Setpoint	Soak	Average
Average NOx, LB/MMBtu	0.145	0.226	0.479	0.283
Improvement, pct	35.0	21.5	(1.5)	13.7
Average Firing Rate, MMBtu/hr	25.4	21.1	9.8	18.8
Improvement, pct	47.3	47.1	55.7	48.8
Average NOx, LB/hr	3.68	4.77	4.69	4.38
Improvement, pct	65.8	58.5	55.0	59.8

Particulates

Particulate samples were collected from the furnace through the gas sampling ports since the flue was no longer in operation. The average particulate emission rate was 0.234 LB/hr, 93.7% lower than the baseline.

Fuel Consumption and Productivity

The average fuel consumption and productivity for no. 6 furnace were calculated from monthly furnace performance reports using data from November 1, 1999 to April 24, 2000. The average fuel consumption was 2.00 MMBtu/ton, 60% lower than baseline. The oxygen rate was 2,597 scf/ton. On days when the furnace was firing, average production was 5.96 tons/hr. This is 3% higher than the baseline, but the increase is not statistically significant. When tons were reported (i.e., excluding heat-up periods), the average firing rate was 11.7 MMBtu/hr.

Again, there is a discrepancy between the fuel rate calculated from the 3 one-hour NOx analyses and the monthly averages. As before, this discrepancy can best be resolved by increasing the weighting given to the measurements taken during soaking.

Equipment Performance

Coke oven gas is a by-product fuel and is a less expensive fuel than natural gas, but burning coke oven gas increases maintenance costs related to the deposition of hydrocarbons and condensate from coke oven gas. In general, the increased maintenance costs are justified by the price difference between coke oven gas and natural gas. However, as the fuel rate in the furnace drops with oxy-fuel combustion, the savings from coke oven gas use shrink.

The oxy-fuel equipment performed well with coke oven gas with two exceptions, the burner refractory tile and the fuel gas check valves. The original burner refractory tile was made from a 60% alumina material. With natural gas firing, the tile showed no signs of wear of degradation over 12 months of operation. However, when the furnace was switched to coke oven gas, excessive wear was seen around the fuel port, and the block had to be replaced after 2 weeks of operation. A 95% alumina material was used for the replacement block, and this block lasted 6 months. This is an acceptable lifetime, but still less than desired. The apparent cause of the degradation is the deposition and later reaction of coke oven gas condensates within the fuel port. Similarly, the fuel gas check valve requires frequent maintenance with coke oven gas, although it operates without trouble on natural gas. Again the apparent cause is condensate from the coke oven gas.

These increased maintenance costs are minor compared to the savings from oxy-fuel operation. However, they do have a significant impact on the relative economics of coke oven gas operation relative to natural gas operation, as discussed below.

Discussion

Operating Economics

The operating costs for the baseline and the oxy-fuel cases were calculated from the internal Burns Harbor valuation for coke oven gas and the current oxygen price. Using the saving less oxygen cost) are 40 percent of baseline operating costs, totaling more than \$200,000 per year. Using the coke oven gas cost for the second half of 2000 the cost reduction would be approximately \$450,000 per year.

As noted above, oxygen-coke oven gas operation does lead to some increased maintenance costs. In the past, increased maintenance with coke oven gas was justified by the lower cost of coke oven gas relative to natural gas. However, with the 60% fuel saving achieved with oxy-fuel, the benefit from the lower cost of coke oven gas is significantly less. This reduced cost differential must be balanced against the additional cost of two sets of refractory tiles per year and additional furnace downtime, plus the expense of monthly check valve maintenance. Assuming that tile replacement can be accomplished within scheduled maintenance outages, the lower cost of coke oven gas relative to natural gas continues to outweigh the cost of this added maintenance.

Air Infiltration

NOx performance in the No. 6 in/out furnace is limited by the rate of air infiltration into the furnace and the associated high nitrogen levels. The problem is especially troublesome at low firing rates where the NOx generation rate (LB/MMBtu) is essentially the same with oxy-fuel as with air-fuel.

The comparable levels of NOx at low fire are understandable considering the high nitrogen level in the furnace at that point. shows the calculated nitrogen level in the furnace vs. firing rate. Also shown are the expected values for stoichiometric combustion with air and with oxygen. At low firing rate, the furnace atmosphere is essentially the same as for air firing, and so, it is not surprising that NOx results are similar in the two cases.

The air infiltration during baseline tests was estimated from the measured levels of excess oxygen and compared with the infiltration calculated for oxygen firing.

A number of different strategies were investigated during this project to improve the door seal. The main problem with the door seal is warping of the door as it heats and cools through operating cycles. Door designs that minimize warping also tend to have lower strength and thermal shock resistance and fail prematurely. While an improved door design would significantly improve NOx performance, an acceptable solution has not yet been found.

Conclusions and Summary

The No. 6 in/out batch furnace at the 160" plate of Bethlehem Steel Corporation's Burns Harbor Division was converted to low NOx oxy-fuel burners based on Praxair® Dilute Oxygen Combustion technology. Four burners with a total firing capacity of 24 MMBtu/hr were installed and operated on coke oven gas. Fuel reductions of 60% over baseline air burner operation were achieved. Slab heating was satisfactory when burner firing was biased toward the door-side of the furnace. Significant levels of air infiltration through gaps in the furnace doors limited improvements in NOx emissions, especially at low furnace firing rates. Nonetheless, a 60% reduction in NOx was achieved. Particulate emissions were 94% lower with the oxy-fuel system. Fuel (coke oven gas) costs, including oxygen costs, were 40% lower than baseline fuel costs, totaling \$200,000 annually based on 1998 fuel costs, or \$450,000 annually based on July-December 2000 fuel costs. These savings were reduced slightly by increased burner block and check valve maintenance costs. No burner block degradation or check valve maintenance was required after 12 months of operation on natural gas. However, the cost advantage of coke oven gas over natural gas is sufficient to justify the additional maintenance on these items.

These results compare favorably against the demonstration goals:

- **Fuel reduction** – achieved 60% reduction compared with a goal of 45%;
- **Operating cost saving** – achieved net fuel/oxygen cost reduction of 40%;
- **NOx generation** – achieved 60% reduction compared with a goal of 70%;
- **Heating quality** – maintained comparable uniformity, heating rate, and mill productivity.

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