Nitrogen Oxides (NO_x) Formation and Control in an Electric Arc Furnace (EAF): Analysis with Measurements and Computational Fluid Dynamics (CFD) Modeling

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A computational fluid dynamics (CFD) model of an electric arc furnace (EAF) has been developed and validated against measurements at the EAF combustion gap. Modeled processes include fluid flow, combustion reactions, radiative heat transfer, turbulence, and NO_x formation. This model is used to identify the NO_x formation mechanisms and to analyse potential NO_x control strategies.

The model successfully predicts the NO_x emission trends. NO_x formation is primarily due to N₂ from air ingress through the slag door or roof ring gap, flowing into the high temperature regions near the burners. N₂ in the oxygen supply is also important. NO_x levels correlate with N₂ and O₂ levels in the furnace. Reducing N₂ and excess O₂ in the furnace is recommended for NO_x abatement. Unlike many combustion devices, controlling temperature is not recommended for reducing NO_x emissions. Large reductions in NO_x emissions are predicted by (in order of importance, from highest to lowest): controlling exhaust flows to limit air ingress, closing the slag door and increasing the purity of the oxygen supply.

KEY WORDS: NO_x; CFD; modeling; EAF; pollution control.

1. Introduction

The emission of nitrogen oxides (NO_x) is an important environmental concern due to its role in the formation of photochemical smog and acid rain. Most NO_x emissions result from the high temperature oxidation of nitrogen during combustion processes. Combustion processes that occur during steelmaking can form NO_x; these processes include cokemaking, reheat furnaces, blast furnaces, basic oxygen furnaces and electric arc furnaces. The U.S. iron and steel industry annually emits 126 000 metric tons of NO_x.¹⁾ This paper focuses on NO_x formation and control for electric arc furnaces (EAF).

Steel mills typically use the EAF to produce steel from returned steel, and sometimes, alternative iron sources such as direct reduced iron. The EAF is a batch process with a cycle time of about 1 to 2 h. Electrical energy is supplied *via* the graphite electrodes and is usually the largest energy contributor in melting operations. Chemical energy is typically supplied from natural gas *via* burners and from graphite or coal *via* lances or bulk addition. The largest source of nitrogen is typically air ingress through the slag door.

The steel industry currently faces increased regulatory pressure to reduce NO_x emissions.²⁾ The 1990 Amendments to the U.S. Clean Air Act have imposed new emission requirements for EAFs located in non-attainment

areas. Relatively little information is available in the open literature on steel industry's NO_x emissions. Agarwal and Jessiman³⁾ state that EAF emit 0.27 kg NO_x/net metric ton of steel. The U.S. EPA reports that EAF release 0.25–0.3 kg NO_x/ton.⁴⁾ A study of 15 different EAF plants found a wide range of NO_x emission data (0.02 to 0.4 kg/ton).⁵⁾

Nitrogen Oxides (NO_x) are a class of air pollutants that include nitric oxide (NO), nitrogen dioxide (NO₂) and nitrous oxide (N₂O). The principal component of NO_x is NO, typically comprising 90%. There are three principal formation mechanisms for NO_x: Thermal, Prompt and Fuel NO_x. The first formation mechanism is very temperature sensitive and hence NO_x formed *via* this mechanism is called "Thermal NO_x." The NO_x is formed from the oxidation of atmospheric nitrogen. This mechanism is insignificant below temperatures of 1 600 K (2 500°F), above which the NO_x formation rate increases exponentially with temperature. Within an EAF, oxy-fuel burners and the arc create the highest temperature regions. "Prompt NO_x" is produced in fuel rich flames through a mechanism involving carbon-hydrogen fragments and is typically not as important as "Thermal NO_x". Many fuels such as coal and heavy fuel oil contain nitrogen. When the fuel is oxidized during combustion, a substantial fraction of the fuel bound nitrogen can also oxidize forming NO_x. NO_x formed *via* this mechanism is called "Fuel NO_x." The high temperatures in the EAF suggest that Thermal NO_x is the dominant formation

mechanism.

There are four ways of controlling Thermal NO_x formation: reduce the temperature, the nitrogen concentration, the oxygen concentration and the dwell time of the gases at the peak temperatures. Thermal NO_x formation is very temperature sensitive and therefore many combustion devices control NO_x formation by reducing the peak temperatures by adding more mass per unit heat release. These strategies include exhaust gas recirculation (common in cars and boilers), high excess air and steam injection (common in gas turbines). Temperature control is not recommended for EAFs as high gas temperatures are needed to melt the steel.

Most combustion devices consume large amounts of air; hence there is an ample supply of nitrogen. However, EAFs do not purposely inject air; therefore reducing the air ingress into the furnace is an attractive strategy. This requires sealing the furnace as much as possible and operating at slightly positive pressure. Air and other sources of nitrogen should be kept out of the hot spots including the arc and the oxy-fuel burners.

A third potential NO_x control strategy is to reduce the oxygen concentration. NO_x formation is greatly reduced in a reducing environment. This is implemented in many combustion devices by staging the air injection. The fuel is initially burnt fuel rich. Then some energy may be extracted to reduce the temperature. Then air is rapidly injected to fully oxidize the fuel and to rapidly lower the temperature. This process is called "staged combustion" and is common in large coal boilers. The EAF already uses staged combustion. Any NO_x formed in the lower half of the furnace will be reduced if the upper half of the furnace has a reducing environment. Combustible gases can then be burnt off at the combustion gap. Available information suggests that the combustion gap is not a significant source of NO_x.

The above mentioned knowledge of NO_x formation suggests that preventing air inflow and operating slightly fuel rich is the best procedure to control NO_x in an EAF. Preventing NO_x formation in the EAF is especially important because of the difficulties of post furnace NO_x removal. The most common method of removing NO_x from a gas stream is to inject ammonia, which reduces the NO_x to N₂. The reactions can occur on a catalyst in a process called Selective Catalytic Reduction (SCR) or in the gas phase in a process called Selective Non-Catalytic Reduction (SNCR). The successful application of either of these processes to EAF steelmaking will represent a significant challenge. The catalyst of the SCR process operates at 570 to 720 K and is prone to fouling with dust and poisoning by a number of compounds. The SNCR process operates only within a relatively narrow temperature range (approx. 1 200 to 1 360 K). The wide variations of EAF off-gas temperature make this a complex control problem.

Furnace models help evaluate the effectiveness of process changes and reduce the number of costly field trials. Computational fluid dynamics (CFD) modeling predicts fluid properties such as flow velocities, temperatures, species and pressures, by solving the fundamental governing equations over a grid that represents the physical geometry. CFD is especially useful for situations, such as an EAF, where experimental measurements are difficult to perform due to the harsh environment. Modeling provides in-

sight into how the NO_x is formed and what the major sources are. CFD modeling also allows one to rapidly test a large number of potential control options.

This paper reports the results of a CFD model of a full scale EAF. Detailed measurements on an industrial EAF helped validate this CFD model. Sensitivity analyses on estimated parameters were also conducted.

2. Methodology

A computational fluid dynamics model of an existing electric arc furnace was developed using finite volume based CFD software.⁶⁾ The EAF was modeled as a quasi-steady state process rather than as a fully transient process, which would require a massive computational effort. This is a reasonable simplification as the time scale of the flows through the furnace is much shorter than the time scales of the process changes. The model geometry for the CFD simulations is derived from an existing EAF, from which the furnace offgas chemistry has been sampled. The furnace geometry is represented by 82 000 tetrahedral cells as shown in **Fig. 1**. The boundaries included the furnace walls, roof, the liquid steel bath, and the combustion gap. The electrodes, burners, roof ring gap, 4th hole gap and slag door were included. Only periods when there is relatively little solid scrap above the slag layer are modeled. This allows only a single phase to be modeled which maintains reasonable computation times. Therefore, the liquid steel bath and solid steel were excluded.

The main features of the model are summarized in **Table 1**. The P-1 radiation heat transfer model is used because an EAF has a high optical thickness. This model accounted for the effects of surfaces, gases and particles. Compressibility effects, viscous heating and buoyancy were assumed negligible. Tests were performed to evaluate these model assumptions and are discussed in latter sections.

Combustion is modeled using both the Eddy-Dissipation Concept to account for turbulent mixing and finite reaction rates for chemical kinetics. Seven species (CH₄, CO, CO₂, H₂, H₂O, O₂, N₂) and a four-reaction reduced mechanism were used to describe the oxidation of methane and carbon monoxide:

Fig. 1. Model geometry showing the exhaust duct, burners and the slag door.

Table 1. Main features of the model.

Properties	Assumption/Model
Density	Incompressible ideal gas law
Mixture heat capacity	Mixing-law
Species heat capacities	Piecewise-polynomial functions of temperature
Mixture thermal conductivity	Ideal-gas-mixing-law
Species thermal conductivities	Constant (not a function of temperature)
Mixture viscosity	Ideal-gas-mixing-law
Species viscosities	Sutherland's law as a function of temperature
Buoyancy effects	Assumed negligible
Turbulence	Standard k-ε turbulence model w/ viscous heating assumed negligible
Radiation	P-1 radiation model with the Weighted-Sum-of-Gray-Gases cell based model for calculating the absorption coefficient. Scattering coefficient is set to be 0.1m^{-1} and accounts for the effect of the EAF dust particles.
Combustion	Eddy-dissipation and finite rate with a five-reaction reduced mechanism
NOx formation	NOx formation using prompt NOx and thermal NOx assuming partial equilibrium for O_2 dissociation

Table 2. Combustion reaction rate constants in Arrhenius form.

Reaction	A_k (kmol, m, s units)	β_k	E_a (J/kmol)
(1) Forward	6.8×10^{15}	-1	167,357,014
(2) Forward	2.75×10^9	0	83,678,507
(2) Reverse	9.56×10^7	0	52,400,000
(3) Forward	3.0×10^9	0	125,517,761
(4) Forward	4.4×10^{12}	0	125,517,761

This mechanism is derived from a reduced mechanism suggested by W. P. Jones and R. P. Lindstedt.⁷⁾ Note that reaction (2) is reversible but reaction (1) is not in order to reduce convergence problems. **Table 2** lists the reaction rate constants given in the Arrhenius form.

NOx is predominately made up of nitric oxide (NO). Nitrogen dioxide (N_2O) is typically an order of magnitude less than NO. For the purposes of this paper, we will assume that the NOx emissions can be predicted from the NO emissions. NO can be formed by the thermal or prompt reaction mechanisms, however, the thermal mechanism is generally predominant. The extended Zeldovich thermal NO mechanism is used:

The reaction rates are obtained from Hanson and Salimian.⁸⁾ The OH radical concentration is given by the re-

lationship of Baulch *et al.*⁹⁾ The O radical concentration is assumed to be in partial equilibrium with O_2 . The N radical concentration is determined by making the quasi-steady assumption whereby its rate of consumption becomes equal to its rate of formation.

The values of the boundary condition parameters are based on actual measurements, the mass and energy balance calculations of the EAF process model DECSIM,¹⁰⁾ literature sources, and engineering estimates in the absence of other data. These parameters are summarized on **Table 3**. A turbulence intensity of 5% is used for all flow boundaries. The slag layer is a source of carbon monoxide which flows up from the liquid steel. Its flowrate is determined from lance and CoJet oxygen flowrates as well as the DECSIM mass and energy balance calculations.¹⁰⁾ The CoJet is a special type of burner with multiple annuluses, in which the center jet (also called the primary) supplies high-pressure oxygen for decarburization. The surrounding two annuluses act as a burner, which maintains the coherence of the oxygen stream due to expansion of the combustion gases during reaction. The methane, oxygen and nitrogen in these two outer annuluses are assumed to remain in the gas phase above the slag layer. It is assumed that all of the oxygen from the primary jet in the CoJet penetrates the slag layer. The slag door and roof ring flowrates are determined by pressure balance. The electrodes are expected to have a

Table 3. Boundary conditions.

Boundary	Property	Value and/or Source
Furnace walls, furnace roof and exhaust duct walls	Temperature Emissivity	1300 K 0.3
Electrodes	Walls	Adiabatic
Electrode Holes	Water flowrate Water Temperature	Estimated 1500K
Slag Layer	CO flowrate Temperature Emissivity	Estimated from lance oxygen and carbon flowrates 1950K 0.6
Burners and Co-jets	Methane, oxygen and nitrogen flowrates	Taken from measured flowrates assuming oxygen has 6% N ₂ by mass
Roof Ring Gap	Air flowrate	Pressure boundary determines air flowrate.
Exhaust	Flow out of furnace	Taken from measured flowrates at fan with combustion gap flow estimated using DECSIM ⁽¹⁰⁾
Slag Door	Air flowrate Temperature Emissivity	Pressure boundary determines air flowrate. 1300 K 0.3

Fig. 2. Measured concentration profiles with times of modeled cases shown.

temperature similar to the gas phase temperature and thus no heat transfer is assumed to occur between the gas phase and the electrodes. Water is sprayed onto the electrodes to prevent them from oxidizing. This water is assumed to have converted to steam as it enters the furnace.

3. Results and Discussion

3.1. Measurement Data

A comprehensive database of an industrial EAF's input, exhaust and operational parameters were measured and recorded. Input parameters included natural gas, oxygen, carbon flows to the furnace's lances and burners. Operational parameters included slag door and roof opening and

closings. Furnace exhaust measurements at the elbow included NOx, CO, CO₂, H₂, O₂ and N₂ species concentrations. Water is removed before the gas composition measurement. These measurements are shown in Fig. 2.

The furnace exhaust measurements highlight some interesting observations about the NOx emissions. The NOx level is often very low with brief periods when high levels are reached. The NOx concentration briefly surpasses 2710 ppm, the upper limit of the analyzer, near the end of the furnace cycle. This is probably due to the slag door being open during that time to take samples prior to tapping. The large amounts of air entering through the slag door result in excess oxygen conditions along with plenty of nitrogen. However, during much of the furnace operation, the NOx

concentration is below 50 ppm. High levels of H_2 and CO are observed in the exhaust, peaking at 20% and >50% respectively. As both are reducing gases, the H_2 and CO levels move in tandem and in the opposite direction of the O_2 levels. The NOx level generally moves in tandem with the O_2 and in the opposite direction of the CO and H_2 . The exception is near the beginning of the heat (16:15); NOx formation at this point may be effected by the exposed arc. The peak NOx levels also occur at high N_2 levels. However, the correlation between NOx and N_2 is not as clear as between NOx and O_2 . Integrating over the 55-min cycle, 77% of the NOx is produced in less than 7 min. These results indicate that NOx can be reduced by eliminating excess oxygen conditions and that the process modifications for NOx reductions need only occur over a small fraction of the cycle time.

3.2. Model Validation

The furnace database, discussed above, was used to validate the NO predictions of the CFD model. The model predictions are evaluated at four times during the heat. Cases 1 through 4 occurred at 16:23, 16:26, 16:56 and 16:59, respectively, as shown in Fig. 2. These four cases consist of two pairs, in which each pair consists of two cases separated by 3 min during which a process change occurred that affected the NO levels. This is done to evaluate if the model can predict the effect of the process change. The first pair occurred at the end of the first charge while the second occurred during the refining stage. Between cases 1 and 2, the natural gas flowrate to the oxy-fuel burner was cut in half which increased the burner's percent excess oxygen from 37 to 180%; the lance oxygen flowrate was reduced which lowered the CO flowrate rising from the slag layer by 57%; and the three Cojets reduced their natural gas flowrate by 18% and their oxygen flowrates by 6%. This process change increased the O_2 and N_2 levels and reduced the CO and H_2 levels. Between cases 3 and 4, the slag door was opened; and the lance oxygen flowrate was reduced which lowered the CO flowrate rising from the slag layer by 61%. This process change also increased the O_2 and N_2 levels and

reduced the CO and H_2 levels.

The most important criterion of the model is its ability to predict the quantities of NO leaving the furnace. **Figure 3** presents a comparison of the NO predictions and measurements for the four cases. Although exact agreements between predicted and measured values are not achieved, Fig. 3 indicates that the model predicted the four cases with reasonable accuracy and the model echoed the trends in the measured data. The over prediction of NO in cases 1 and 3 may be due to the NO model not considering the reduction of NO by the reducing gases CO and H_2 . Improving the model accuracy would require validating the predicted furnace temperatures and exhaust flowrates. No furnace temperature data is available. Temperature measurements, even at the elbow duct exit, are difficult to obtain. Although the flow at the exhaust fans is known, the flow through the combustion gap is not. The model used a constant flowrate exiting the furnace that was calculated using an estimated combustion gap flowrate. The exhaust flowrate and temperature affect the furnace temperature and the oxygen and nitrogen levels, which determine the rate of NO formation.

The furnace temperature field is a key determinant of the NO formation rate. **Table 4** presents the exhaust and average furnace temperature predictions for the four cases. The average furnace temperatures are slightly higher than the exhaust temperatures since the gases lose heat to the walls and are diluted with air ingress from the roof ring as they move up through the furnace. Measured temperatures at the exhaust are not available and a temperature range based on the calculated data from a mass and energy balance model [10] is used to evaluate the predictions in lieu of more exact values. Case 2 has the lowest exhaust temperature. **Table 5** shows that this is due to the large amounts of air ingress coming through the roof ring. Case 4 has lower temperatures than case 3, again due to increased air ingress but this time coming in through the slag door.

The species concentration, especially nitrogen and oxygen, are also important determinants of the NO formation rate. The species concentrations at the exhaust are shown in mole percentages in **Table 6**. The model successfully predicts the trends, in particular whether or not the furnace has excess oxygen. However, the predicted values are not always quantitatively exact, most likely due to the lack of

Fig. 3. Comparison of NO predictions and measurements.

Table 5. Mass flows (kg/s) across various boundaries.

Case	Flow of Air Ingress through Roof Ring Gap	Flow of Air Ingress through Slag Door	Burner 1, Cojets, Slag Layer	Exhaust
1	2.92	—	3.53	6.45
2	4.03	—	2.42	6.45
3	2.39	—	4.06	6.45
4	0.09	3.70	2.66	6.45

Table 4. Validation of furnace temperatures.

Case	Exhaust Temperature		Predicted Average Furnace Temperature
	Predicted by Model	Estimated from Experience	
1	1877 K	1600 K to 1900K	1894 K
2	1486 K	1600 K to 1900K	1745 K
3	1798 K	1600 K to 1900K	1898 K
4	1593 K	1600 K to 1900K	1684 K

Table 6. Exhaust species mole percentages.

Species	Case 1		Case 2		Case 3		Case 4	
	Model	Actual	Model	Actual	Model	Actual	Model	Actual
	mole %	mole %	mole %	mole %	mole %	mole %	mole %	mole %
CH ₄	0	NA	0	NA	0	NA	0	NA
O ₂	0	0	8	4	0	0	8	6
CO	10	18	0	1	4	31	0	1
CO ₂	33	23	19	18	35	18	21	16
H ₂ O	10	15	27	24	22	15	27	24
H ₂	13	11	0	0	6	8	0	0
N ₂	33	32	46	54	33	27	43	54

Table 7. Sensitivity analyses.

Case 4			Avg. Furnace Temperature	Avg. Exhaust Temperature	[NO]
	Baseline		1684	1593	1411
Slag Layer Temperature	1950K	-20 %	1557	1500	1102
		+20 %	1847	1717	3036
Wall Emissivity	0.2	-20 %	1701	1618	1436
		+20 %	1678	1583	1399
Wall Temperature	1300K	-20 %	1665	1545	1380
		+20 %	1726	1676	1487

precise flow rates at the slag layer, exhaust and slag door boundaries. The most significant difference was for the prediction of the CO level in case 3. The model over predicted the oxidation of CO to CO₂ and the nitrogen levels. This suggests that the model over predicted the air ingress through the roof ring. The exhaust flowrate is not well known due to the lack of flow data for the combustion gap where additional air is drawn into the exhaust ducting. However, the model correctly predicts the trends due to the process changes that occur from case 3 to case 4.

3.3. Analysis of Modeling Assumptions

Some simplifications and assumptions must be made when modeling the complex phenomena present in an EAF. This section discusses the appropriateness and legitimacy of these modeling assumptions.

Compressibility effects are encountered in gas flows at high velocity and/or in which there are sizeable pressure variations. The model used the incompressible ideal gas law, neglecting compressibility effects due to the high computational costs. In all 4 cases, over 99% of the cells have Mach numbers less than 0.1 and therefore compressibility effects can be neglected.

Buoyancy of the hot air in a furnace can induce natural convective flows. In this work, the buoyancy of the fluid was neglected to lower computation times. To check this assumption, the Grashof number divided by the Reynolds number squared can be used to determine the importance of buoyancy forces in a mixed convection flow. If this ratio approaches or exceeds unity, strong buoyancy contributions to the flow can be expected. In cases 1, 2, 3 and 4, 99%, 98%, 98% and 91% of the cells had a ratio less than 0.25. The largest values of the ratio are found near the slag layer boundary, which is expected due to the low velocities and high temperatures in this region.

Radiation is an important heat transfer process. The P-1 radiation model is used in this work as the medium is considered to be optically thick and this model also allows for scattering. If the optical thickness is less than 1, the medium is optically thin and the P-1 model is not very accurate.

In all 4 cases, more than 93% of the cells had an optical thickness greater than 2, therefore the P-1 model is appropriate.

A number of the boundary condition parameters in the model had to be estimated. Sensitivity analyses are performed on the slag layer temperature, wall emissivity and wall temperature in order to evaluate their effect on the NO predictions of case 4. Each parameter mentioned is varied separately by $\pm 20\%$ and the changes in the average furnace, exhaust temperature predictions and NO concentration are shown in **Table 7**. The simulations indicate that the model is the most sensitive to slag layer temperature. A 20% increase in the slag layer temperature increased the NO levels in the EAF exhaust by 115%. The sensitivity of the NO levels to the exhaust flowrate and the percent nitrogen in the oxygen is evaluated in the NO control section below.

3.4. NO Formation

Information about the formation of NO in the EAF furnace is essential for the development of effective NO control strategies. Thermal NO formation occurs when nitrogen and oxygen are raised to high temperatures. This is illustrated in the NO, O₂, N₂ and peak furnace temperatures profiles of case 3. In case 3, the slag door is closed and the main flow features result from the air inflow from the roof ring and the hot, swiftly moving gases from the burner and Co-Jets. The peak NO levels, shown in **Fig. 4**, occur near the burners and Co-jets. This corresponds to the location of the peak temperatures, shown in **Fig. 5**. Oxygen levels are highest near the burners and the roof rig. Nitrogen levels are highest near the roof rig gap and are low in the lower furnace. In this case, burners 2 and 3 are turned off. Nitrogen and oxygen, entering through the burners, Co-Jets and especially the roof ring, flow through the peak temperature regions and form NO.

The highest NO levels occurred in case 4. The differences between case 3 and case 4 result from the opening of the slag door and reduced lancing into the slag layer. The slow moving air entering through the slag door as well as

Fig. 4. Mass fraction of NO for case 3.

Fig. 7. Temperature profile for case 4.

Fig. 5. Temperature profile for case 3.

Fig. 8. Mass fraction of O₂ for case 4.

Fig. 6. Mass fraction of NO for case 4.

Fig. 9. Mass fraction of N₂ for case 4.

the high-speed burner and Co-Jet gases dominate the furnace flow. Little air enters through the roof ring gap as shown in Table 5. Peak NO levels are again near the burner and Co-Jets, as shown in Fig. 6. However, the changes in NO levels between cases 3 and 4 are not due to temperature changes. The hot regions created by the burners and Co-Jets are not greatly affected as illustrated in Fig. 7. In fact, the process changes from case 3 to case 4 reduced the average furnace temperature, as shown in Table 4. As shown in Figs. 8 and 9, the higher levels NO for case 4 are due to the higher levels of nitrogen and oxygen in the lower furnace. This nitrogen and oxygen enters through the slag door and flows through the peak temperature regions, where the NO is formed.

Each source of nitrogen atoms for the formation of NO was separately tracked, in order to study the source of nitrogen during the formation of NO. These sources included burner N₂, Co-Jet N₂, slag door N₂, and roof ring N₂. The first two sources are due to the presence of nitrogen (estimated to be 6%) in the oxygen supply. The later two sources are due to the ingress of air. Figure 10 presents, for case 4, the relative contribution of the nitrogen sources that contributed to NO present in the EAF exhaust. These results show that the slag door is the main source of nitrogen for the formation of NO in case 4. However, the nitrogen in the oxygen supply is significant, contributing 21% of the nitrogen.

The NO formation model considers both thermal and prompt NO formation mechanisms. In case 4, the thermal and prompt NO mechanisms formed 1 420 and 86 ppm NO respectively for a total of 1 506 ppm. Thus, prompt NO contributes only 6% of NO in case 4 and thus is not an impor-

tant source of NO.

Both the furnace measurements and modeling suggest that the NO formation in an EAF is more a function of the N₂ and O₂ levels than the temperature. This is contrary to many combustion devices but provides attractive opportunities for NO reduction.

3.5. NO Control Strategies

Most combustion devices reduce NO by reducing the peak combustion temperatures. However, in an EAF this is undesirable, as it will slow down the steel melting process. Fortunately as discussed above, the NO formation is a strong function of nitrogen and oxygen levels. This suggests that methods to reduce nitrogen and excess oxygen be investigated. Eleven additional process conditions are modeled to evaluate potential NO reduction strategies. The process changes are listed in Tables 8 and 9. Cases 5a to 5e are identical to case 4 except that the slag door is closed and the exhaust flowrate is progressively reduced. Cases 6a to 6d investigate the effect of oxygen purity. Cases 7a and 7b examine the effect of reduced exhaust flow and oxygen purity when the slag door is open. Case 8 investigates the effect of reduced exhaust flow and oxygen purity relative to case 2. Case 9 looks at the effect of additional oxygen injection (post combustion). Figure 11 shows that reducing the exhaust flow for case 4 with the slag door closed, steadily reduces the NO levels. This is due to the reduced amount of air coming into the furnace. The lower levels of oxygen result in increased CO levels. However the CO levels can be burnt at the combustion gap. The NO levels of case 5e (*i.e.* lowest exhaust flow) can be further reduced by decreasing the amount of nitrogen in the oxygen supply as shown in Fig. 12. The model suggests that NO reductions of 96% are possible. However, there does not appear to be a large benefit in lowering the nitrogen levels below 3% for the case modeled.

The results are summarized in Fig. 13; note the log scale for NO. There is a strong correlation between nitrogen inputs into the furnace and NO emissions. Lowering the ex-

Fig. 10. NO sources for case 4.

Table 9. NOx control strategies—Description of process changes for case 2.

	Slag Door	Exhaust Flow Rate (kg/s)	Oxygen Purity
Case 2	Closed	6.45	94% O ₂ , 6% N ₂
Case 8	Closed	2.75	100% O ₂ , 0% N ₂

Table 8. NOx control strategies—Description of process changes for case 4.

	Slag Door	Exhaust Flow Rate (kg/s)	Oxygen Purity
Case 4 (Baseline)	Opened	6.45 (Baseline)	94% O ₂ , 6% N ₂ (Baseline)
Case 5a	Closed	Baseline	Baseline
Case 5b	Closed	5.475	Baseline
Case 5c	Closed	4.50	Baseline
Case 5d	Closed	3.525	Baseline
Case 5e	Closed	2.75	Baseline
Case 6a	Closed	2.75	97% O ₂ , 3% N ₂
Case 6b	Closed	2.75	100% O ₂ , 0% N ₂
Case 6c	Closed	Baseline	100% O ₂ , 0% N ₂
Case 7a	Open	Baseline	100% O ₂ , 0% N ₂
Case 7b	Open	2.75	100% O ₂ , 0% N ₂
Case 9	Closed	2.995	Baseline

Fig. 11. Effect of exhaust flow rate on NO and CO levels for the slag door closed (cases 5a–5e).

Fig. 12. NO concentration as a function of oxygen purity for cases 5e, 6a and 6b.

Fig. 13. NO versus N_2 input for NOx cases 2, 4, 5, 6, 7 and 8.

haust flow lowered the nitrogen inputs and the NO emissions for cases 2 and 4 with slag door closed. However, closing the slag door without lowering the exhaust flow was not effective (case 5a). Also, lowering the exhaust flow without closing the slag door was also not optimum (case 6b versus 7b). Increasing the oxygen purity lowered the nitrogen inputs and the NO emissions for cases with high (5a) and low (5e) exhaust flowrates. There was no good correlation between NO emissions and temperature. There was a partial correlation between NO emissions and oxygen inputs, however this could not explain the effect of increasing

Fig. 14. The effect of exhaust flowrate and post-combustion on average furnace temperature.

the oxygen purity.

The strong correlation between NO and nitrogen inputs provides EAF designers and operators with a clear strategy for reducing NO emissions. This is consistent with existing NO formation control methods for EAFs which include air ingress prevention and slightly fuel rich operation of the furnace⁵; the last item requires better sealing of the furnace and operating slightly positive pressure. The recommended strategy is to close the slag door, better seal the furnace, reduce the exhaust flowrate and increase the oxygen purity.

3.6. Furnace Energy Efficiency

The recommended NOx strategy of closing the slag door, sealing the furnace and reducing the exhaust flowrate can also provide energy efficiency benefits. Furnace temperature profiles show that the open slag door of case 4 creates a low temperature region in the lower furnace due to the inflow of air. This low temperature region will reduce the efficiency of melting and heating the steel. In case 3, the closed slag door provides a consistently hot lower furnace. For cases 5a–5e, Fig. 14 shows that reducing the exhaust flow increases the average furnace temperature by reducing the amount of excess air inflow. However, a maximum furnace temperature is reached after which the lack of oxygen for complete combustion starts reducing the furnace temperature. By adding additional oxygen through the burners (case 9), the furnace temperature can be further increased. However, there is an increase in NO emissions unless the burners use high purity oxygen. This suggests that implementing the NO control strategies developed in this paper can also improve the overall furnace energy efficiency.

4. Conclusions

The CFD model of the EAF accurately predicted the trends observed in the NOx exhaust concentration measurements. The model and measurement data provide insight into NOx formation mechanisms:

- The majority of NOx is formed in a small fraction of the total furnace operating time. Therefore, process changes for NOx control need only be implemented for short durations of the total time.
- NOx levels correlate with N_2 and O_2 in the exhaust. An inverse correlation with CO and H_2 levels is observed.

Therefore, maintaining reducing conditions in the furnace is needed to reduce NO_x levels.

- NO_x levels do not correlate with temperature changes in the furnace.
- NO_x formation is primarily due to N₂ from air ingress through the slag door or roof ring gap, flowing into the high temperature regions near the burners. N₂ in the oxygen supply is also important.

Unlike many combustion devices, controlling temperature is not recommended for reducing NO_x emissions. Reducing N₂ and excess O₂ is recommended. Large reductions in NO_x emissions are predicted by (in order of importance):

- Controlling exhaust flows to limit air ingress and maintain reducing furnace conditions.
- Closing the slag door.
- Increasing the purity of the oxygen supply.
- Monitoring offgas chemistry on a continuous basis and control of oxygen and fuel injection to maintain a slightly reducing furnace atmosphere.

These NO_x control strategies should also provide energy efficiency and conversion cost reduction benefits.

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