Numerical Simulation of Raceway Formation in Blast Furnace

Tyamo Okosun, Guangwu Tang, Dong Fu, Armin K. Silaen, Bin Wu, and †*Chenn Q. Zhou

Center for Innovation through Visualization and Simulation
Purdue University Calumet
2200 169th Street
Hammond, IN 46323

*Presenting author: czhou@purduecal.edu
†Corresponding author: czhou@purduecal.edu

Abstract
Pulverized Coal Injection (PCI)/ Natural Gas (NG) co-injection has a significant impact on the size and shape of the raceway inside a Blast Furnace. Consequently, this affects the gas distributions, as well as iron ore reduction, and the furnace pressure drop. The raceway size and shape are influenced by incoming gas momentum entering the raceway envelope from the tuyere jet, the combustion of coke and injected fuels, coke particle size, fuel injection rates, slag volume, and other complex factors. A 3-D CFD mathematical model has been established for estimating the raceway geometry and combustion inside the blast furnace. This model considers the effects of coke combustion and injection fuels on the raceway geometry and the raceway gas flow patterns. The combustion effects are treated as additional source terms of mass and momentum in the gas phase because the combustion converts solid fuels into the gaseous phase and releases heat. In this paper, the raceway geometry and raceway combustion models are presented, along with the methodologies for raceway simulation, and some selected model applications (including parametric study analyses of blast furnace operation under a variety of fuel injection conditions).

Keywords: Ironmaking, blast furnace, Raceway, PCI, CFD

Introduction

The injection of pulverized coal into the blast furnace is a crucial technology for lowering hot metal production costs and reducing coke consumption. In order to achieve high injection rates and coke replacement ratios, the combustion process of injection fuel and the fluid dynamics inside the raceway must be well understood and documented.

The thermodynamics and kinetics of coal and coke combustions under laboratory conditions are well published, and, based on this fundamental knowledge, mathematical modeling can be conducted to simulate injected fuel and coke combustion inside the blast furnace raceway. Additionally, numerical modeling can be utilized to optimize furnace operation conditions in an effort to achieve higher fuel injection rates and optimal coke replacement ratios. Early in published model development, some simulations of the raceway regions assumed one-dimensional plug flow for the tuyere and the raceway. However, these early models, in many cases, failed to properly predict the de-volatilization process and combustion of released volatiles [1, 2]. In certain two-dimensional models [3], the combustion of coal and coke in the raceway were considered, however the turbulent features of the gas phase were either ignored or simplified [4]. Additionally, these two-dimensional models were mostly applied to simplified raceway shapes, such as cylinders or spheres. For more realistic scenarios, three-dimensional modeling is needed to simulate the full raceway geometry, the combustion of injected fuels and coke, and the fluid flow phenomena inside the raceway envelope.

Accurate modeling of the raceway is important, because it contains the critical parameters that control gas distribution in the blast furnace. Kawabata et al [5] developed a one-dimensional raceway mathematical model designed to predict the gas temperature and composition distributions inside the raceway region. In this model, coke particles inside the raceway were treated as a continuous phase. Additionally, the raceway depth and the void fraction inside raceway were assumed to be constant. Hatano[6] and Nogami [7] developed a two-dimensional model with a similar approach. However, it was also reported that raceway sizes obtained in pseudo two-dimensional and real two-dimensional apparatuses could be different. In the pseudo two-dimensional model, a jet of air is injected through a tuyere placed in the longitudinal central plane of the model domain. The jet can expand in all directions after leaving the tuyere tip, however, it is assumed that any impacts on flow due to jet expansion in the perpendicular direction to the tuyere axis are negligible. Moreover, the combustion of injection fuel has significant effects on the size and shape of raceway of a blast furnace, a phenomena which has not been well examined by any of the aforementioned modeling techniques.

In this paper, an established three dimensional (3-D) computation fluid dynamics (CFD) mathematical model for simulating the raceway shape and combustion in a blast furnace is examined. This model was developed through the efforts from the Global R&D-East Chicago of ArcelorMittal and Purdue University Calumet. In this model, the effects of coke and injected fuel combustion on the raceway geometry and the raceway gas flows are considered. The combustion of injected fuels and coke convert solid mass into a gaseous phase and generate heat in the raceway. The increase in the gaseous mass will increase the gas volume, and the increase in the temperature will expand the gas volume and/or increase the pressure. Therefore, in the modified 3-D CFD raceway model, source terms are added accordingly to present the effects due to these increases.

Mathematical Model

The simulation is divided into two major portions: (a) simulation of NG/PC combustion inside the tuyere, and (b) simulation raceway formation and combustion. The simulation starts with the NG/PCI combustion simulation. The flow profiles at the tuyere outlet obtained from this simulation are used as inlet boundary conditions in the raceway model. The commercial CFD solver ANSYS Fluent is used to model flow inside the blowpipe/tuyere geometry, as well as the initial stages of NG/PC combustion inside the tuyere region as shown in Figure 1.

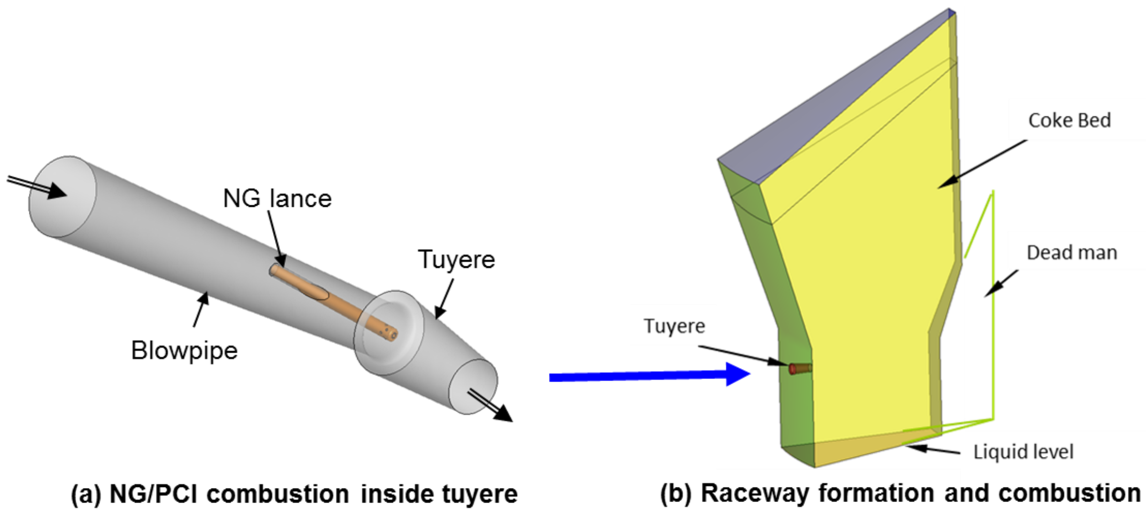

Figure 1. Schematic of CFD models of the tuyere and the raceway

The raceway model is divided into two sub-models, (a) the raceway formation model and (b) the raceway combustion model. A methodology has been developed to predict the effects of the combustion on the raceway geometry (sizes and shapes).

The raceway model estimates the raceway geometry and the distributions of coke injection fuels in the raceway. The model determines the raceway size and shape based on the porosities of the active coke zone at the front of a tuyere. The outputs of the raceway formation model are then used as boundary conditions for the raceway combustion model to prescribe a flow domain and porosity map.

The raceway combustion model employs a Eulerian approach to describe the gas-particle flow and combustion of the injected fuel and coke inside the raceway envelope. Conservation equations are utilized to describe mass transfer, heat transfer, and the motion of gas and particles.

The combustion of injected fuels and coke have an impact on the raceway geometry in two ways, (a) mass transfer from solid to gas, and (b) gas volume expansion due the temperature increase. To account for these phenomena and their effects on the raceway shape and size, mass and volume are added to each local cell accordingly. The mass and gas volume increments determined by the combustion are fed cell by cell to the formation model. The formation model will then determine a new raceway shape and size with the increments taken into account. Table 1 lists the detailed procedure of this methodology. The commercial CFD solver ANSYS Fluent and a proprietary CFD code are used in this study.

Table 1. Iteration between raceway formation and combustion models

Step	Model	Simulator	Raceway geometry and combustion simulating status
1	Raceway Formation	ANSYS Fluent®	To predict raceway without combustion
2	Raceway Combustion	Proprietary Code	Combustion simulating with raceway geometry from Step 1
3	Raceway Formation	ANSYS Fluent®	To predict raceway with combustion source term from Step 2
Repeat Steps 2 and 3 till the shape and size converges.			

Raceway Formation Model

A transient 3D Eulerian approach was employed to predict the raceway geometry. In the Eulerian approach, the different phases are treated as interpenetrating continua. The Eulerian approach uses the concept of phasic volume fraction, α. The volume fractions are assumed to be the continuous functions of space and time, and the sum of the fractions is equal to one. The conservation equation for each phase is given below,

$$\frac{\partial(\alpha_i \rho_i \phi)}{\partial t} + div(\alpha_i \rho_i \phi u) = div(\Gamma grad\phi) + S_\phi \tag{1}$$

where S_ϕ is the mass transfer between the two phases due to chemical reactions of coal and coke. The flow behavior of the fluid-solid mixture is described using a multi-fluid granular flow model. The granular multi-fluid model consists of granular phase conservation equations and fluid phase conservation equations. The inter-phase momentum exchange is modeled using the Syamlal-O'Brien model [8], where the fluid-solid interaction coefficient is defined using an empirical relationship based on terminal velocity measurements in fluidized beds and settling beds. The coefficient is a function of volume fraction and Reynolds number. The solid-solid interaction is based on the assumption that there is instantaneous binary collisions between particles and that the energy dissipation is due to inelasticity of collisions.

Raceway Combustion Model

The proprietary in-house model uses an Eulerian system to describe the gas-particle flow and coal combustion. Conservation equations of mass, energy, and momentum are used to describe the mass transfer, heat transfer, and the motion of gas-particle, respectively. The k- ε two-phase turbulence model is used to simulate gas and particle turbulence. The eddy break-up-Arrhenius combustion model is used for gas combustion. Two-competing reaction model is used for the coal devolatilization rate [9]; and the diffusion-kinetic model is used for the overall reaction rate of char reaction.

Governing equations

Gas-particle phase continuity, momentum, species mass fraction, and energy equations, as well as the equations of the turbulence momentum and its dissipation rate at steady state are described below.

$$\frac{\partial}{\partial x}(\rho u \phi) + \frac{\partial}{\partial y}(\rho v \phi) + \frac{\partial}{\partial z}(\rho w \phi) = \frac{\partial}{\partial x}(\Gamma_\varphi \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(\Gamma_\varphi \frac{\partial \phi}{\partial y}) + \frac{\partial}{\partial z}(\Gamma_\varphi \frac{\partial \phi}{\partial z}) + S_\varphi + S_{\varphi Pg} \tag{2}$$

$$\begin{aligned} &\frac{\partial}{\partial x}(\rho_P u_P \phi_P) + \frac{\partial}{\partial y}(\rho_P v_P \phi_P) + \frac{\partial}{\partial z}(\rho_P w_P \phi_P) \\ &= \frac{\partial}{\partial x}(\Gamma_{\varphi P} \frac{\partial \phi_P}{\partial x}) + \frac{\partial}{\partial y}(\Gamma_{\varphi P} \frac{\partial \phi_P}{\partial y}) + \frac{\partial}{\partial z}(\Gamma_{\varphi P} \frac{\partial \phi_P}{\partial z}) + S_{\varphi P} + S_{\varphi Pg} \end{aligned} \tag{3}$$

where ϕ and ϕ_P are the general independent variable, Γ_φ and $\Gamma_{\varphi P}$ are the effective transport coefficient; S_φ, $S_{\varphi P}$ and $S_{\varphi Pg}$ are source terms.

Interphase momentum exchange

The particle exchanges momentum with the gas through the drag force. When the void fraction is greater than or equal to 0.8, the momentum exchange coefficient is expressed as,

$$\beta_k = \frac{3}{4} C_D \rho \frac{|u - u_k|(1-\varepsilon_k)^2}{d_k} f(\varepsilon_k) \tag{4}$$

$f(\varepsilon_k)$ accounts for the effect of the presence of other particles and is a correction to the Stokes law for free fall of a single particle. The following equation is used in this work.

$$f(\varepsilon_k) = (1-\varepsilon_k)^{-3.8} \tag{5}$$

The drag coefficient is estimated as a function of the Reynolds number and is described as follows.

$$C_D = \begin{cases} \frac{24}{Re_k}\left(1 + \frac{Re_k^{0.667}}{6}\right) & Re_k < 1000 \\ 0.44 & Re_k \geq 1000 \end{cases} \tag{6}$$

where the Reynolds number is given by

$$Re_k = \frac{\rho d_k |u - u_k|}{\mu} \tag{7}$$

When the void fraction is less than 0.8, the momentum exchange coefficient is calculated by the Ergun's equation below.

$$S_u = (150\frac{(1-\varepsilon_g)^2 \mu_g}{\varepsilon_g \psi_c^2 d_b^2} + 1.75\frac{|U_g - U_b|(1-\varepsilon_g)\rho_g}{\psi_c d_b}) \times \varepsilon_g (U_g - U_b) \tag{8}$$

Gas combustion

The eddy break-up turbulent combustion model is used to quantify the effect of turbulence on the combustion rates of volatiles, carbon monoxide, and hydrogen. The reaction rate is determined as

$$W_s = \min(W_{s,\,EBU}, W_{s,Arr}) \tag{9}$$

where

$$W_{s,Arr} = B_s \rho^2 Y_F Y_{ox} \exp(-\frac{E_s}{RT}) \tag{10}$$

$$W_{s,EBU} = C_R \rho \frac{k}{\varepsilon} \min(Y_F, \frac{Y_{ox}}{\beta}) \tag{11}$$

Interphase heat transfer

The heat transfer between a single reacting particle and the gas phase is calculated based on the stagnant film theory.

$$Q_k = \pi d_k Nu_k \lambda_s (T - T_k) \frac{B_k}{\exp(B_k) - 1} \tag{12}$$

$$B_k = -\frac{\dot{m}_K C_{ps}}{\pi d_k Nu_k \lambda_s} \tag{13}$$

$$Nu_k = 2 + 0.5 \mathrm{Re}_k^{0.5} \tag{14}$$

where the so-called 1/3 Law is used to calculate the thermal conductivity and around the coal particles.

Moisture evaporation rate

A diffusion model is used to calculate the moisture evaporation rate. The moisture in a coal particle is assumed to diffuse to the surface of the particle to form a liquid film. This film is treated as a surface layer of a water droplet with the same diameter. The moisture evaporation rate is calculated as follows.

$$\dot{m}_{wk} = \begin{cases} -\pi d_k Nu_k D_s \rho_s \ln\left(1 + \frac{Y_{H_2O,s} - Y_{H_2O,g}}{1 - Y_{H_2O,s}}\right) & T_k < T_b \\ -\pi d_k Nu_k \frac{\lambda_s}{C_{ps}} \ln\left(1 + \frac{C_{ps}(T - T_k)}{1 - L_w}\right) & T_k \geq T_b \end{cases} \tag{15}$$

$$Y_{H_2O,s} = B_w \exp(-E_w / RT_k) \tag{16}$$

where Y_{H2O} is mass fraction of vapor at the surface of the particle. The Nusselt number, Nu_k, is calculated as

$$Nu_k = 2 + 0.5 \mathrm{Re}_k^{0.5} \tag{17}$$

Coal devolatilization rate

Coal is assumed to decompose to form char and combustible volatiles. The combustible volatile is assumed to consist of hydrocarbons (C_dH_d) and carbon monoxide.

$$\text{Coal} = [\text{Volatiles}] + \text{Char} \tag{18}$$

$$C_aH_bO_c = [C_dH_b + cCO] + eC \ (\text{Volatiles} = C_dH_b + cCO) \tag{19}$$

The constants a to e are determined from the coal ultimate analysis.

The coal devolatilization rate is proportional to the mass of the dry ash free (daf) coal. The devolatilization is modeled by two simultaneous competing first-order irreversible reactions.

$$daf\ coal \begin{cases} (1-\alpha_1)\ Ch_1 + \alpha_1 V_1 & (Reaction1) \\ (1-\alpha_2) Ch_2 + \alpha_2 V_2 & (Reaction2) \end{cases} \tag{20}$$

The devolatilization rate is calculated as

$$\dot{m}_{vk} = -\alpha_1 m_{dk} B_{v1} exp(-\frac{E_{v1}}{RT_k}) - \alpha_2 m_{dk} B_{v2} exp(-\frac{E_{v2}}{RT_k}) \tag{21}$$

where α_1 is obtained from the volatiles matter percentage in coal proximate analysis, and α_2 is equal to $2\alpha_2$.

The reduction rate of the daf coal mass due to the devolatilization is calculated as

$$\dot{m}_{dk} = -m_{dk} B_{v1} exp(-\frac{E_{v1}}{RT_k}) - m_{dk} B_{v2} exp(-\frac{E_{v2}}{RT_k}) \tag{22}$$

The volatile matters released into the gas phase undergo the following homogeneous combustion.

$$C_d H_b + \frac{d}{2} O_2 = d\ CO + \frac{b}{2} H_2 \tag{23}$$

$$2CO + O_2 \rightarrow 2CO_2 \tag{24}$$

$$2H_2 + O_2 \rightarrow 2H_2O \tag{25}$$

Char reaction rate

The following heterogeneous char reactions are included in the model.

$$C + O_2 \rightarrow CO_2 \tag{26}$$

$$2C + O_2 \rightarrow 2CO \tag{27}$$

$$C + CO_2 \rightarrow 2CO \tag{28}$$

$$C + H_2O \rightarrow CO + H_2 \tag{30}$$

All the char reactions are assumed to be of first-order with respect to O_2, CO_2, and H_2O. The reaction rates for char reactions in equations (26) to (30) in terms of the gas consumption rates are given below.

$$\dot{m}_{ck,A} = -\pi d_k^2 \rho_s Y_{O_2,s} B_A \exp(-\frac{E_A}{RT_k}) \tag{31}$$

$$\dot{m}_{ck,B} = -\pi d_k^2 \rho_s Y_{O_2,s} B_B \exp(-\frac{E_B}{RT_k}) \tag{32}$$

$$\dot{m}_{ck,C} = -\pi d_k^2 \rho_s Y_{CO_2,s} B_C \exp(-\frac{E_C}{RT_k}) \tag{33}$$

$$\dot{m}_{ck,D} = -\pi d_k^2 \rho_s Y_{H_2O,s} B_D \exp(-\frac{E_D}{RT_k}) \tag{34}$$

Applications

The existing raceway models have been applied to analyze a variety of blast furnaces in a broad range of operating conditions. In this paper, two recent analysis projects utilizing the computational raceway simulation model are examined. Both simulation projects detailed herein were previously published and presented at AISTech 2015 [10][11]. The first furnace examined was the No. 1 blast furnace at United States Steel Canada Lake Erie Works. The project was undertaken to study injected natural gas (NG) combustion performance and the impact of various lance designs on blast furnace operation and stability.

Research was conducted on three lance designs. The first, referred to as the 'fast lance' had a large number of small holes for gas egress. The design of this lance was expected to improve gas dispersion and enhance combustion inside the tuyere region. The second lance was a simple straight pipe, and the third design was a modification of the fast lance, created by boring out the lance tip. The three lances can be observed in Figure 2.

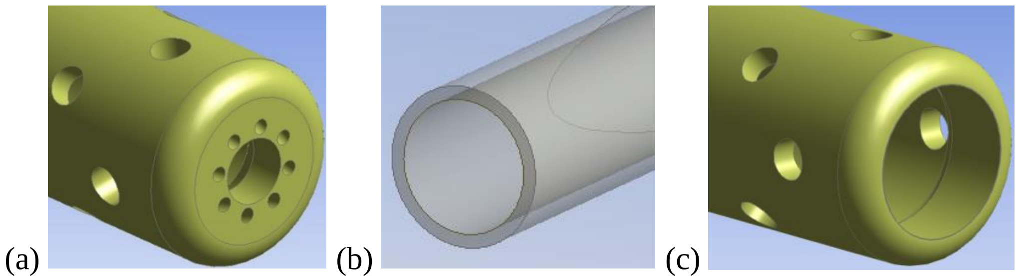

Figure 2. (a) Fast Lance, (b) Straight Lance and (c) Bored Lance

Identical operating conditions were maintained in all three lance design simulations so that combustion characteristics could be accurately compared. After calibrating the kinetics of natural gas combustion (to accurately model flame liftoff and blowout), combustion of injected natural gas inside the tuyere was modeled [12]. Combustion characteristics and temperature profiles inside the tuyere were examined to compare combustion speed between the three lance designs. A comparison between temperature profiles inside the tuyere is shown in Figure 3.

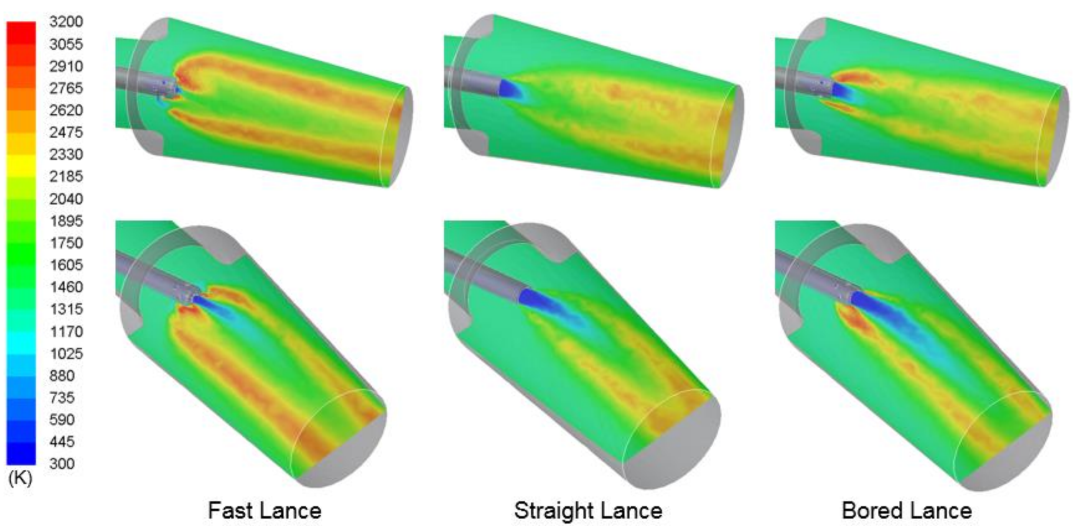

Figure 3. Temperature distributions in the tuyere

It is obvious from an examination of the temperature profiles that the additional holes in the lance tip in bored lance and fast lance designs contribute to the enhancement of combustion inside the tuyere. The increased mixing and combustion inside the tuyere also leads to the release of additional CO and CO_2 in the gas flow that enters the raceway. The fast lance leads significantly more reactions than the other two designs, with the difference between the bored and straight lances being relatively minor. Figure 4 details the CO_2 distribution inside the tuyere for each lance design.

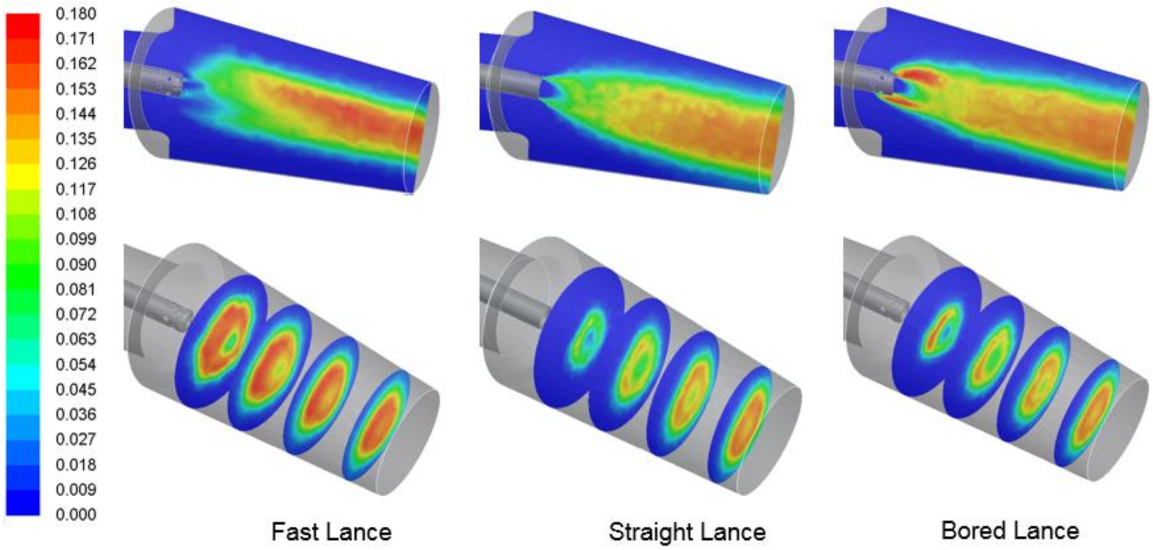

Figure 1. CO_2 mass fraction distribution inside the tuyere

The additional combustion observed in the fast lance case results in higher pressure drops over the tuyere region. Plant operators observed that higher NG injection rates also resulted in increased pressure drops, which can lead to limitation on furnace wind and production rates. Due to this, the increased pressure drop in the fast lance case, when utilized at high production rates, can result in poor stability due inability to supply enough wind to the furnace.

The raceway shape is not significantly impacted by the lance design, however gas species and temperature distributions are heavily altered. As visible in Figure 5, high gas temperatures are present on the side of the raceway, due to the angle at which NG is injected into the tuyere and the resulting consumption of oxygen. With more oxygen available on one side of the raceway, the gas temperatures increase due to coke combustion.

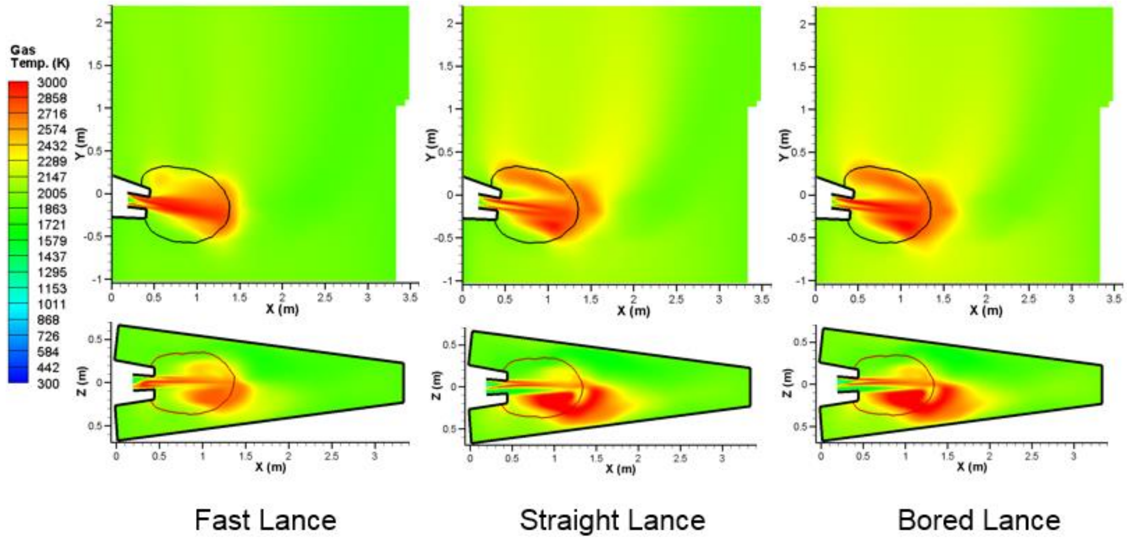

Figure 5. Temperature distribution in the raceway, side view (top) and top view (bottom)

Based on the raceway model outlet temperatures and gas distributions, data was then exported to a second in-house CFD code known as the blast furnace shaft simulator. This additional model allowed for the examination of blast furnace operation in the stack. Minor variations in gas and temperature distribution, as well as overall gas utilization in the furnace provided the basis for selecting improved operating conditions for the Lake Erie Works blast furnace.

The second furnace examined was located at AK Steel Dearborn Works in Dearborn, MI. This project was performed to examine the impact of co-injecting pulverized coal (PC) and NG in a variety of operating conditions on combustion and furnace performance [11]. One of the key factors examined in this project was the use of NG as a carrier gas for PC. The hope was that the replacement of nitrogen with NG could possibly improve combustion performance, in an effort to avoid some of the difficulties in the use of high rate pulverized coal injection, such as reduced permeability. Initially, a baseline case was modeled at standard operating conditions provided by AK Steel Dearborn Works. It was quickly discovered that the baseline design of the tuyere region resulted in poor heat transfer between NG combustion and the PC particles. Additionally, as can be observed in Figure 6, the method of NG injection (a tuyere port) leads to increased thermal wear on the tuyere surface.

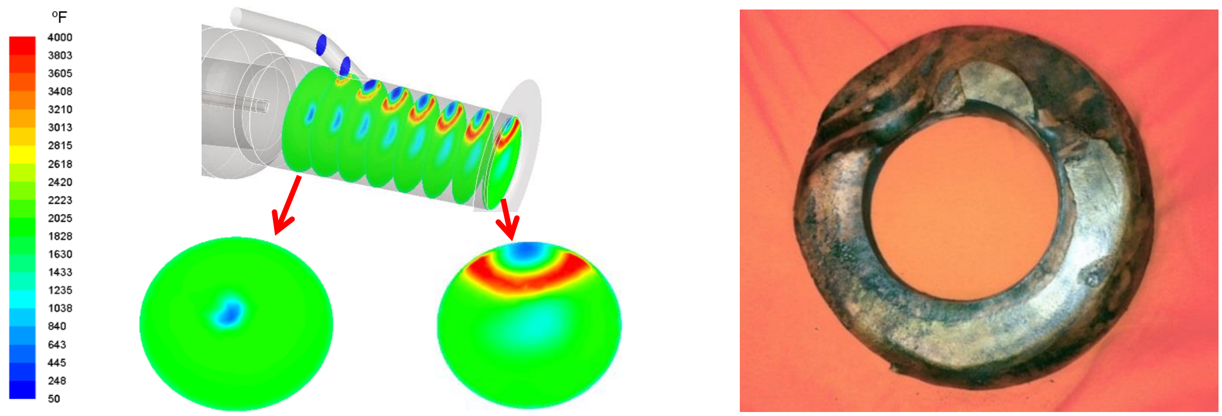

Figure 6. Temperature contours located on planes through the tuyere (left) and sectioned nose piece of tuyere from AK Steel Dearborn Works with wear/ablation zones visible (right)

The gas flow from the tuyere produces a standard jet into the raceway, with gas velocities lower at the center due to the momentum required to accelerate the pulverized coal. Areas of recirculation are easily visible in the raceway envelope, with regions of high temperature present in the recirculation areas as shown in Figure 7.

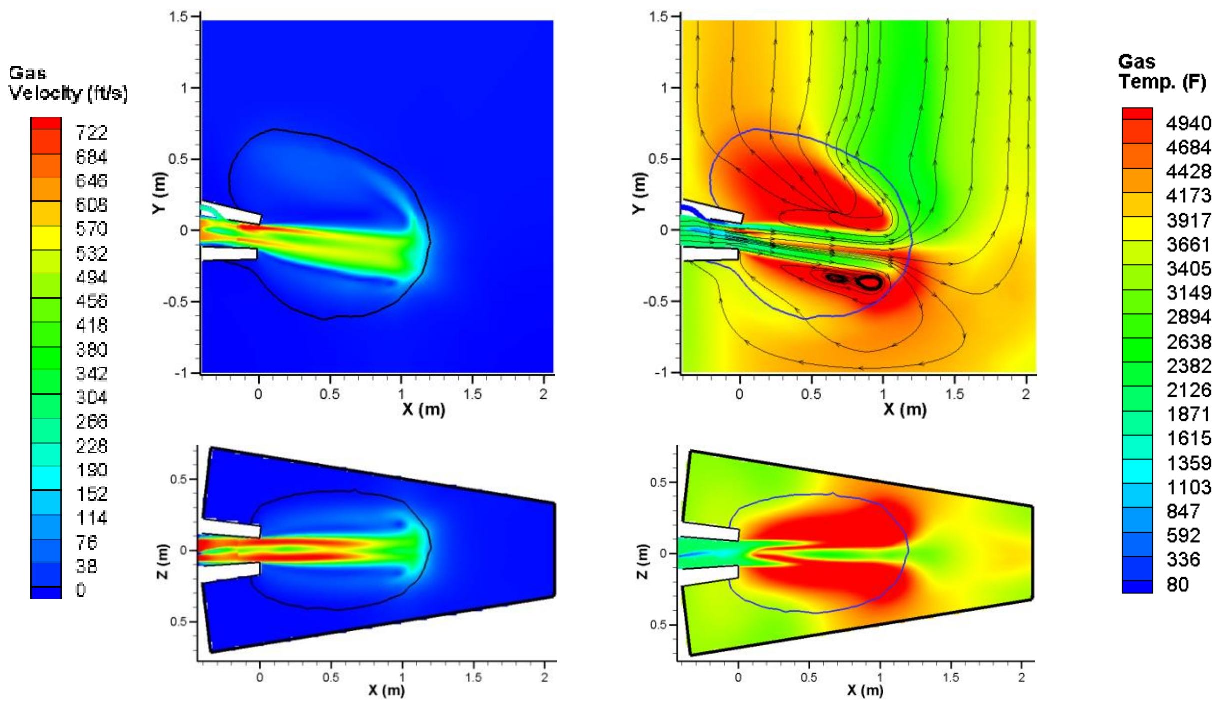

Figure 7. Contours of gas velocity (left) and gas temperature with streamlines (right) in the raceway region. Upper contours are located on section A-A, lower contours located on section B-B.

A key finding of this study was the discovery of incomplete PC burnout in the raceway. As seen in Figure 8, in some regions, the burnout reaches only 60% before passing out of the raceway envelope and into the coke bed. This phenomena can also result in performance and stability issues in furnace operation to unburnt coal buildup in the blast furnace coke bed.

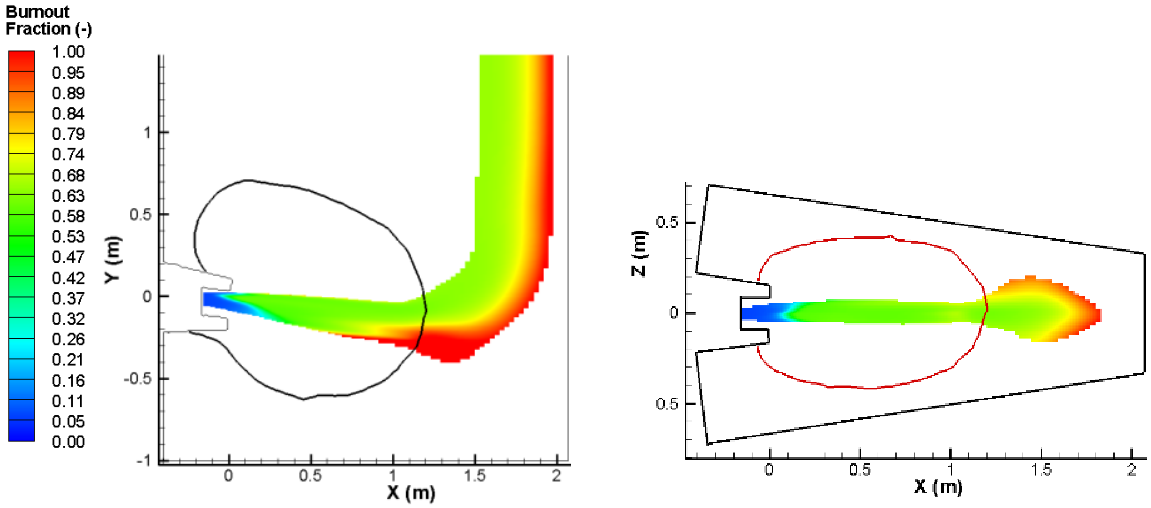

Figure 8. Contours of pulverized coal burnout fraction through the raceway viewed from the side (left) and top (right).

A variety of simulation cases were modeled in the study, utilizing two different gas injection designs, as well as the modification of the PCI carrier gas from nitrogen to natural gas. It was determined that the total burnout rate was improved for all cases that utilized NG to convey PC into the furnace. With the addition of a secondary lance for NGI, the thermal wear problem could be easily resolved. Additionally, when utilizing both the secondary NGI lance and NG for the conveyance of PC, the total fuel burnout neared 96%, a significant increase over standard operating condition values.

These two projects provide a representative examination of the broad applications of the blast furnace raceway modeling capabilities developed. Ranging from design modification and troubleshooting, to operational capabilities and combustion performance analysis, the existing model has been well validated and applied across a number of analyses for a variety of steel producers and their blast furnaces.

Conclusions

A 3-D CFD mathematical model has been established for estimating the raceway geometry and combustion in the raceway, in which the effects of coke and injected fuel combustion on the raceway geometry and gas flow/species distribution through the raceway envelope are considered. The combustion effects are treated as additional source terms of mass and momentum in the gas phase, because combustion serves to convert solid mass into gaseous mass and contribute to the generation of heat, resulting in additional momentum. The simulation results indicate that combustion has significant effects on the raceway shape and size.

The raceway model can be utilized to complete parametric studies analyzing natural gas and coal combustion in the raceway, raceway geometry, raceway gas flow, raceway temperature, raceway gas compositions, and other parameters. The parametric studies examined using this model thus far have helped to optimize to tuyere operation, coal and coke properties to achieve high fuel injection rates, improve fuel replacement ratios, and enhance PCI performance in a variety of ironmaking facilities and operating conditions.

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