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Optimization of Raceway Parameters in Iron Making Blast Furnace for Maximizing the Pulverized Coal Injection (PCI) Rate

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Abstract

This paper presents a method by which the maximum possible rate of pulverized coal injection (PCI) in blast furnace can be predicted. The method is based on a two-step approach. First, a first principle simulation model of the blast furnace is used to generate data sets for the development of a linear model of pulverized coal injection rate. The data has been generated randomly in MATLAB software within the range of operating parameters (constraints) of the blast furnace. After that, the coefficients of the function have been determined. The inputs and the resulting outputs formed the data on which the linear optimization model was developed. Next, the linear model was used for maximizing the pulverized coal rate injection by optimizing the other variables. Two operating Indian Blast Furnaces have been chosen to validate the optimization model.

Keywords

Raceway Parameters, Blast Furnace, Optimization, PCI

1. Introduction

Reduction of fuel consumption, increase of the blast furnace capacity and productivity are the main factors, which determine the development of the iron making industry. The decrease of coke rate is the most important factor for reduction of hot metal production cost as well as from environmental perspectives. This problem can be resolved by improvements in utilization of gas heat and reduction potential by rationalizing gas distribution in the furnace cross-section. In recent iron making blast furnaces, pulverized coal is increasingly injected as a supplementary fuel in replacement of coke [1]. However, there have been several problems experienced during past practices of coal injection worldwide.

There are several problems in blow pipes and tuyeres due to low combustibility of coal compared to oil and natural gas. The former would have unburnt coal particles trapped in the coke bed interstices and change the gas stream distribution in the burden. This leads to problems in tuyere and blow pipe failures [2]. This can be rectified with proper injection conditions, coal characteristics and coal injection rate.

Few investigations have been performed related to coal combustion efficiency in terms of coal properties and blast conditions. Yamaguchi *et al.* [3] investigated ignition and combustion of coal particles in the blow pipe zone theoretically. Optimum location of injection lance was investigated by Nomura and McCarthy [4]. They also investigated blow pipe coal ash deposition problem using simple combustion model and concluded that the gas diffusion is dominant factor for combustion rate. Andersson *et al.* [5] studied the optimization model for the burden distribution calculation of the blast furnace process. Azadeh and Ghadheri [6] studied integrated modeling and optimization of blast furnace. This model is capable of driving to optimum solutions by a rule-based mechanism. The model was verified and validated using robust statistical and structural analysis.

Pettersson *et al.* [7] have developed an optimization method for iron making in the blast furnace with the aim to minimize costs and CO_2 emissions. This method is based on genetic algorithm. Discrete element method analysis of blast furnace and solids motion around raceway was studied by Natsui *et al.* [8]. Theoretical study on the maximum injection rates of pulverized coal in iron making blast furnace was investigated by Nomura and Callot [9]. They have taken some assumptions like coal burnout in raceway zone and no coal ash deposition in blowpipe wall. Their prediction was 190 - 210 kg/thm in some operating blast furnaces. They have also investigated coke consumption with respect to certain parameters like oxygen enrichment and moisture addition. Gostenin *et al.* [10] studied the operation of a group of blast furnace by redistribution of the available energy resources. They have improved the blast furnace operation by optimizing natural gas and oxygen consumption. Top gas recycling was optimized by Ghanbari and Saxen [11]. They concluded the optimal states for top gas recycling. Selections of PCI coals using Blast Furnace models have been done by Benette [12]. The model was also used to know the impact of high ash coal on the operating cost of blast furnace. Danloy *et al.* [11] have developed a blast furnace model to optimize the burden distribution with respect to other parameters of the blast furnace. The aim of the study was to improve the operation.

So far, no concrete work has been done to know the maximum coal injection rate in blast furnace due to complex nature of raceway phenomena including combustion of coke and coal particles. In previous investigation [1], the authors have studied theoretically the coal combustion in the blow pipe tuyere region. The theory has been confirmed with reported experiments in reasonable agreement.

In the present study, an optimization model has been developed for the prediction of maximum possible rate of pulverized coal and optimum blast parameters for specified condition. The results are examined using some practical data of coal injection in Indian blast furnace. Sensitivity tests of the model parameters are also being conducted in the range of conditions expected in operating blast furnaces.

2. Development of a Linear Process Model

Our final aim was to find the optimization model for pulverized coal injection into the blast furnace. First, we have developed a raceway model. The raceway model is one dimensional and static. It is based on mass and heat balance.

2.1. Reduced Ordered Process Model

The role of reduced order model is to replace the more rigorous mathematical model of a system or a process by a model that is considerably "smaller" than the original multidimensional model; but still describes at least approximately, key aspects of the system of process. Usually this model is one-dimensional and computationally amenable for real time plant applications.

2.1.1. Model Development

The reduced order model of the raceway has been developed for real time applications in an operating blast furnace involving combustion of coke and PC. In order to keep the model computationally tractable and suitable for real time predictions, the following assumptions have been used.

1) One dimensional axisymmetric steady state conditions with radial variation of the process variables (temperature and compositions, etc.).

2) Density, viscosity and diffusivity of the gas depend on temperature and composition.

3) Total fuel rate (coke + PC) has been considered to be constant. This implies that replacement ratio of PC is 1, which essentially indicates that the amount of coke saved is replaced with an equal amount of PC during operation.

4) Combustion of coke takes place only after complete combustion of pulverized coal.

The molar flow rate of blast has been calculated approximately by the average flow rate of gas before and after combustion under the given operating conditions. Before combustion the flow rate of gas can be expressed as:

$$F_1 = \frac{V_b}{22.4}\left[0.21 + O_{2en}\right] + W_{st} + W_{\mathrm{N}_2} \tag{1}$$

After the combustion of total fuel, the flow rate of gas is:

$$F_2 = \left(N_{\mathrm{N}_2} + N_{\mathrm{CO}} + N_{\mathrm{H}_2}\right) \tag{2}$$

From Equations (1) and (2), the average flow rate of gas (F), based on the cross section of the hearth [13] can be calculated as:

$$F = \frac{2\left(F_1 + F_2\right)}{\pi D_h^2} \tag{3}$$

With regard to the flow rate in the vicinity of the upper boundary, the following approximate relationship between the vertical component F_y, and the horizontal component F_x, can be established at any location along the tuyere axis [14].

$$\frac{F_y}{F} = 2.3erf\left(0.5\frac{F_x}{F} - 2\right) + 2.9 \tag{4}$$

The major quantum of outflow rate of gas through the combustion zone has been estimated by F_y multiplied by an empirical coefficient ξ. This coefficient represents the fractional area of effective outflow surface and is estimated to be 0.25.

2.1.2. Tuyere Combustion Sub-Model (Chemical Kinetics)

The principal combustion reactions occurring in the tuyere zone could be given as:

(i) $C + O_2 \rightarrow CO_2$

(ii) $C + CO_2 \rightarrow 2CO$

(iii) $C + H_2O \rightarrow H_2 + CO$

(iv) $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

The water-gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$) has been neglected since the reaction (iii) is the predominant reaction in the combustion zone.

The species reaction (O_2; CO_2; H_2O; CO and H_2) rate, r_i can be expressed as follows:

$$r_i = \frac{-\varepsilon \mathrm{d}C_{gi}}{\mathrm{d}\theta} = \frac{-\varepsilon \mathrm{d}\left(Py_i/RT_g\right)}{\mathrm{d}\theta} \quad \left(i = 1,2,3,4,5\right) \tag{5}$$

$$r_1 = R_1^* + \frac{1}{2}R_4^* \tag{6}$$

$$r_2 = -R_1^* + R_2^* \tag{7}$$

$$r_3 = -r_5 = R_3^* - R_4^* \tag{8}$$

$$r_4 = -2R_2^* - R_3^* \tag{9}$$

Overall reaction rate may be written as:

$$R^* = k_i C_{gi} \quad \left(i = 1,3\right) \tag{10}$$

The expression for rate constant k_i based on the unit volume of the combustion zone may be presented as:

$$k_i = \frac{1}{\dfrac{1}{k_{fi}a} + \dfrac{1}{\eta_i k_{mi}\rho_b}} \quad \left(i = 1,3\right) \tag{11}$$

The mass transfer coefficient k_{fi} can be expressed as follows:

$$k_{fi} = \left(\frac{D_i}{\phi d_p}\right) Sh \quad \left(i = 1,3\right) \tag{12}$$

The following relationship may be applied to the high Reynolds number (Re_p) region:

$$Sh = 1.5 Re_p^{0.55} \tag{13}$$

The chemical rate constant for reaction (i) of a single carbon particle can be expressed as [13]

$$K_{m1} = 6.53 \times 10^5 \left(a/\rho_b \right) \sqrt{T_m} \exp\left(-22140/T_m \right) \tag{14}$$

The chemical rate constant for reaction (ii) is

$$K_{m2} = 8.31 \times 10^9 \exp\left(-30190/T_m \right) \tag{15}$$

The chemical rate constant for the reaction (iii) is given as

$$k_{m3} = 13.4 T_m \exp\left(-17310/T_m \right) \tag{16}$$

The reaction (iv) is fast among the four chain reactions but it would stop after attaining equilibrium state. The critical oxygen content, y_1^*, may be nearly 5 % with respect to the initial oxygen content during combustion in the tuyere zone. Thus the reaction rate may be expressed as

$$R_4 = R_3 \quad \text{at} \quad y_1 \geq y_1^*, \quad R_4 = 0 \quad \text{at} \quad y_1 < y_1^* \tag{17}$$

2.1.3. Governing Transport Equations

Using the concept of reduced order model, the steady state heat and mass transfer model has been developed in the combustion zone.

A differential one dimensional control volume is considered. On this volume, the mole balance for the total gas flow is given as:

$$\frac{-\mathrm{d}\left(F_x\right)}{\mathrm{d}x} = \frac{4F_y \xi}{D_T} + \left(\alpha \sum_{i=1}^{5} r_i + \beta \sum_{i=1}^{5} r_i \right) \tag{18}$$

The relationship between F_y and F_x has been provided in Equation (4).

For each component of the gaseous species, the mass balance during combustion of pulverized coal and coke can be represented as:

$$\frac{\mathrm{d}y_i}{\mathrm{d}x} = \frac{y_i \left(\alpha \sum_{i=1}^{5} r_i + \beta \sum_{i=1}^{5} r_i \right) - \left(\alpha r_i + \beta r_i \right)}{F_x} \tag{19}$$

The differential heat balance equation incorporating both pulverized coal and coke combustion in an integrated manner can be expressed as:

$$\begin{aligned} \frac{\mathrm{d}T_g}{\mathrm{d}x} = {} & \alpha \left(\frac{\sum_{i=1}^{4} R_i \left(-\Delta H_i \right) + c_{pc} T_c \sum_{i=1}^{3} R_i + c_{pg} T_g \sum_{i=1}^{5} r_i - \pi D_T h_{gc} \left(T_g - T_c \right)}{F_x \left(c_{pg} + T_g \frac{\partial c_{pg}}{\partial T_g} \right)} \right) \\ & + \beta \left\{ \frac{\sum_{i=1}^{4} R_i \left(-\Delta H_i \right) + c_c T_c \sum_{i=1}^{3} R_i - \pi D_T h_{gc} \left(T_g - T_{coal} \right) - \left(H_{dev} * PCI * VM * P_D \right)}{F_x \left(c_{pg} + T_g \frac{\partial c_{pg}}{\partial T_g} \right)} \right\} \end{aligned} \tag{20}$$

The above formulation takes into account bulk transport of heat with gas flow, heat exchange between gas and solid and heat generated by chemical reactions.

The temperature of the coke particles in the combustion zone has been assumed to be related to the surrounding gas temperature [14] as:

$$T_c = 0.8T_g \tag{21}$$

Boundary conditions:

Boundary condition for coke particles at the tuyere nose ($x = 0$);

$$y_{10} = \left(0.21 + O_{2en}\right) \tag{22}$$

$$y_{20} = y_{40} = y_{50} = 0 \tag{23}$$

$$y_{30} = \left(W_{st} * 22.4\right) / \left(18 * 1000\right) \tag{24}$$

$$F_{x0} = F_1 / \left(\pi D_T^2 n / 4\right) \tag{25}$$

$$T_0 = T_b \tag{26}$$

Boundary condition for coal particle at tuyere nose ($x = 0$),

$$y_{10} = \frac{\left(\left(\left(0.21 + O_{2en}\right) * V_b\right) / 22.4\right) - 2 \times VM}{VM + \left(V_b / 22.4\right)} \tag{27}$$

$$y_{20} = VM / \left(VM + \left(V_b / 22.4\right)\right) \tag{28}$$

$$y_{30} = \left(2 * VM\right) / \left(VM + \left(V_b / 22.4\right)\right) \tag{29}$$

$$y_{40} = y_{50} = 0 \tag{30}$$

$$F_{x0} = F_1 / \left(\pi D_T^2 n / 4\right) \tag{31}$$

$$T_0 = T_b \tag{32}$$

where, subscript 0 represents the condition at the tuyere nose.

Numerical solution of the above equations using proper boundary conditions gives radial temperature and composition profile of the gas in the raceway zone of Blast Furnace.

2.1.4. Raceway Penetration Depth Estimation

The following equation has been used to estimate the depth of raceway cavity.

$$\frac{D_R}{D_T} = k_R \left(\frac{\rho_g u_g^2 T_r}{P T_a \rho_b g d_p}\right)^{1/2} \tag{33}$$

where, empirical constant, $k_R = 0.18$ when PCI has been used and $k_R = 0.27$ when only coke has been considered. These constants have been tuned for the present real time model with respect to the plant operating data.

2.2. Objective Function

The ordinary differential equations of the raceway model have been solved using 4th order Runga-Kutta method. The solver algorithm has been implemented in C++ computer code to simulate the process. Numerical simulation of the raceway was carried out using data from literature to establish its predictive capability. Model formulation was suitably modified to match the model output with those reported in literature. Subsequently, data from an Indian operating blast furnace were utilized to tune the adjustable parameters of the reduced order model (heat transfer coefficient between gas and coke, mass transfer coefficient, rate constant of chemical reaction, diffusivity of gas component, etc.) so as to make it amenable for application under Indian blast furnace operating conditions. Subsequent calculations were terminated at the raceway penetration depth (Equation (33)).

The objective function can be expressed in terms of various operational parameter including raceway parameters. Raceway Adiabatic Flame Temperature (RAFT), Steam addition, O_2 enrichment, Blast volume, Blast temperature, Volatile matter in coal and carbon % in coal are the most important parameters of raceway zone of blast furnace. Keeping in mind the parameters, the following linear objective function has been developed from first principle based above model data sets:

$$f(x)_{\max} = a_0 + \sum a_i x_i$$

where a_0, a_i are coefficients and x_i are different process variables.

Subject to: $x_{\min} \le x_i \le x_{\max}$

Where $f(x)$ = PCI rate (kg/thm)

$i = 1$ to 7.

The variables are:

x_1 = Raceway Adiabatic Flame Temperature (RAFT (K));

x_2 = Steam addition (tons/hr);

x_3 = O_2 enrichment (%);

x_4 = Blast volume (Nm^3/min);

x_5 = Blast temp (K);

x_6 = Volatile Matter (VM) in coal (%);

x_7 = Carbon in coal (%).

3. Result and Discussion

Pulverized coal injection (PCI) is an effective way to decrease the amount of coke and environmental problems in a blast furnace. Here, an optimization framework has been developed for the prediction of maximum possible rate of pulverized coal injection and optimum blast parameters for specified conditions. The optimization method is based on a two-step approach. First, a first principle simulation model of the blast furnace is used to generate data sets. The inputs and the resulting outputs formed the data on which the linear optimization model was developed. Next, the linear model was used for maximizing the pulverized coal rate injection by optimizing the other variables using Luus-Jaakola method. Luus-Jaakola is a direct search optimization technique to solve many optimization problems of chemical and biochemical processes. Table 1 presents the ranges of the inputs as well as the numbers of discrete level; every variable is uniformly distributed between its minimum and maximum values. About hundred variable combinations given by the factorial plan were used as inputs to the first principle model.

The results are examined using some practical data of coal injection in two operating Indian blast furnaces. Sensitivity tests of the model parameters are also being conducted in the range of conditions expected in operating blast furnaces. As the goal of the work was to find the maximum rate of pulverized coal injection into the blast furnace, an important step in the analysis was the formulation of raceway model. The raceway model is static and one-dimensional with respect to the coordinate is based on mass and heat balance.

Various operating parameters and their range of two Indian integrated steel

Table 1. Ranges of the inputs as well as the number of discrete levels.

Variables	Range
RAFT (K)	2200 - 2400
Steam addition (t/hr)	0 - 16
O_2 enrichment (%)	0 - 4
Blast volume (Nm^3/min)	3000 - 4200
Blast temperature (˚C)	850 - 1050
Volatile Matter (%)	25 - 30
Carbon in coal (%)	55 - 65

Table 2. Major operating constraints, plant operating variables and their optimized conditions.

Case 1

Variable Constraints
RAFT (K) = 2380 - 2430
Steam (tons/hr) = 4 - 5
O_2 (%) = 2 - 4
Blast Volume (Nm^3/min) = 2350 - 2380
Blast Temperature (K) = 1470 - 1500
VM (%) = 19 - 20
C in PCI (%) = 71 - 72
Output: - Plant values (kg/thm): 118.65 **Optimized PCI (kg/thm): 135**

Variables	Plant Values	Model Output
RAFT (K)	2393	2397
Steam addition (t/hr)	4.14	4.38
O_2 enrichment (%)	2.95	3.08
Blast volume (Nm^3/min)	2360	2353
Blast temperature (˚C)	1473	1486
Volatile Matter (%)	19.24	19.14
Carbon in coal (%)	71.10	71.61

Table 3. Major operating constraints, plant operating variables and their optimized conditions.

Case 2

Variable Constraints
RAFT (K) = 2320 - 2360
Steam (tons/hr) = 2.7 - 3.0
O_2 (%) = 2.8 - 3.0
Blast Volume (Nm^3/min) = 2500 - 2550
Blast Temperature (K) = 1470 - 1500
VM (%) = 19 - 20
C in PCI (%) = 70 - 71
Output:- Plant values: 135(kg/thm) **Optimized PCI (Kg/thm): 146**

Variables	Plant Values	Model Output
RAFT (K)	2333	2355
Steam addition (t/hr)	2.78	2.91
O_2 enrichment (%)	2.91	2.91
Blast volume (Nm^3/min)	2516	2517
Blast temperature (˚C)	1473	1497
Volatile Matter (%)	19.22	19.79
Carbon in coal (%)	70.76	70.23

plant have been taken for investigation. It has been done to testify the model performance. The results have been shown in Table 2 and Table 3. It can be observed from Table 2 (Case 1) that the optimized value is 135 kg/thm compared to current operating value of 118.65 kg/thm with available operating raceway parameters. In Table 3 (Case 2), it can be observed that the current operating PCI is less than the optimized PCI with available operating raceway constraints. Both the plant can charge more PCI with available constraints variables without any problems in the blast furnace. If more than optimized pulverized coal injection (PCI) is charged, then various problems including tuyere burning can happen.

4. Conclusion

An optimization method has been developed for raceway zone of blast furnace to predict the maximum permissible coal injection rate in certain operating blast conditions. It is based on fundamental models of raceway for data generation and an optimization technique. The capability of prediction has been demonstrated by two case studies. The model predictions are reasonably good. The linear objective function has been formulated based on large amount of data. The data has been generated randomly in MATLAB software within the range of operating parameters (constraints). After that, the coefficients of the function have been determined. Two large Indian steel plants have chosen to validate the objective function and to show the results. The designated plants are operating below optimized conditions as per results from optimization technique. This model is in generic nature and can be used in any operating blast furnace to predict maximum permissible PCI rate with available constraints. This work will help to operate the blast furnace with PCI without any difficulty. It will also reduce the cost and maintain steady operation of the blast furnaces.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

a	Specific surface area, (m^2/m^3(bed))
c_{pc}	Specific heat of coke, (J/mol·K)
c_{pg}	Specific heat of gas, (J/mol·K)
C_{gi}	Concentration of gas component, (mol/m^3 (bed))
d_p	Diameter of coke particle, (m)
D_h	Diameter of hearth, (m)
D_R	Raceway depth, (m)
D_i	Diffusivity of gas component, (m^2/sec)
D_T	Tuyere diameter, (m)
V_b	Blast volume in dry base, (m^3/sec)
F	Average flow rate of gas, (mol/m^2·sec)
F_1	Gas flow rate before combustion, (K-mol/sec)
F_2	Gas flow rate after combustion, (K-mol/sec)
F_x	Gas flow rate in x-direction, (K-mol/m^2·sec)
F_y	Gas flow rate in y-direction, (K-mol/m^2·sec)
h_{gc}	Heat transfer coefficient between gas and coke, (W/m^2·K)
ΔH_i	Heat of reaction, (J/mol)
H_{dev}	Heat of volatilization (J/mol)
i	Gas component
k_i	Rate constant of chemical reaction, ($(mol/m^3)^{1-n}$/sec)
k_{fi}	Mass transfer coefficient, (m/K)
k_{mi}	Chemical reaction rate constant, (m^3/mol-sec)
n	No. of tuyere, (–)
N_{CO}	Amount of CO after combustion (K-mol/sec)
N_{H_2}	Amount of H_2 after combustion K-(mol/sec)
N_{N_2}	Amount of N_2 after combustion (mol/sec)
P	Pressure in raceway zone, (K-mol/m sec^2)
P_D	Productivity, (tons/hr)
r_i	Rate of consumption of gas component, (mol/m^3(bed)·sec)
R_i	Rate of reaction, (mol/m^2·sec)
Re_p	Particle Reynolds number, (–)
R	Gas constant (J/K.mol)
Sh	Sherwood number, (–)
T_a	Ambient temperature (K)
T_b	Blast temperature (K)
T_c	Temperature of coke particle, (K)
T_{coal}	Temperature of coal particle, (K)
T_g	Temperature of gas, (K)
T_m	Mean temperature of coke and gas, (K)
T_r	Raceway gas temperature (K)
u_g	Velocity of bosh gas (m/s)
VM	Volatile Matter, (–)

O_{2en}	Oxygen enrichment, (−)
W_{st}	Amount of steam addition, (K-mol/sec)
W_{N_2}	Amount of N_2 (K-mol/sec)
x	Distance in x-direction
y	Mole fraction of gas component, (−)
thm	Ton of hot metal

Greek Letters

η_i	Effectiveness factor, (−)
ρ_b	Bulk density of coke, (kg/m^3(bed))
ρ_g	Density of bosh gas, (kg/m^3)
ξ	Fractional area of the effective outflow surface, (−)
φ	Sphericity of particle, (−)
α	Fraction of coke rate (−)
β	Fraction of coal rate (−)
ε	Voidage of the combustion is zone (−)
θ	Time (sec)