Static and Dynamic Control Model of BOF Steelmaking Process and Its Validation With Steel Plant Data

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INTRODUCTION
The Basic Oxygen Furnace is one of the most widely used routes for the production of steel. The process is autogeneous in nature, i.e. the thermal energy is produced from the reaction between oxygen and silicon, manganese, carbon etc., Carbon reaction being the biggest contributor. In our work, we had developed the static and dynamic control model (based upon waste gas analysis and post-combustion control) to predict the raw material requirement and course of various reactions, slag and metal volume and their compositions and waste generation rates and post-combustion ratio inside the converter. The post-combustion ratio in association with volumetric flow rate of waste gas and their temperatures help to predict the behavior of slag formation which is used to control the dry blow/slopping during the process. The model has been successfully validated using the data of JSW Steel Plant in India.

STATIC CONTROL MODEL
The static model is based upon overall heat and material (Fe, slag, oxygen) balances which calculates the amount of flux (lime), iron ore to be added and volume of oxygen to be blown along with final liquid steel and slag weights for given weights, composition of hot metal, scrap as well as for the given end point conditions. Vice-versa it can also calculate hot metal and scrap weight for other known quantities. These models are based upon feedback control (to adjust the errors arising due to unknown or uncertain part of heat and mass balances).

Mass balance
For mass balance, elements as well as their presence in input/output are given in Table 1.
<table>
<thead>
<tr>
<th>Element</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>Hot Metal</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td>Ore (as Fe₂O₃)</td>
<td>LD Slag (as FeO)</td>
</tr>
<tr>
<td></td>
<td>DRI (as Fe and FeO)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scrap</td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>Hot Metal</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td>Scrap</td>
<td>LD Slag (as SiO₂)</td>
</tr>
<tr>
<td></td>
<td>Ore (as SiO₂)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lime (as SiO₂)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dolomite (as SiO₂)</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>Hot Metal</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td>Ore (as MnO)</td>
<td>LD Slag (as MnO)</td>
</tr>
<tr>
<td></td>
<td>Scrap</td>
<td></td>
</tr>
<tr>
<td>Phosphorous</td>
<td>Hot Metal</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LD Slag (as P₂O₅)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>Hot Metal</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LD Slag</td>
</tr>
<tr>
<td>Carbon</td>
<td>Hot Metal</td>
<td>Steel</td>
</tr>
<tr>
<td></td>
<td>DRI</td>
<td>Off Gas (as CO and CO₂)</td>
</tr>
<tr>
<td></td>
<td>Scrap</td>
<td></td>
</tr>
<tr>
<td>Calcium Oxide</td>
<td>Lime</td>
<td>LD Slag</td>
</tr>
<tr>
<td></td>
<td>Dolomite</td>
<td></td>
</tr>
<tr>
<td>Magnesium Oxide</td>
<td>Ore</td>
<td>LD Slag</td>
</tr>
<tr>
<td></td>
<td>Dolomite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lime</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>Ore (as oxides)</td>
<td>LD Slag (as oxides)</td>
</tr>
<tr>
<td></td>
<td>DRI (as oxides)</td>
<td>Off Gas (as CO and CO₂)</td>
</tr>
<tr>
<td></td>
<td>Lime (as oxides)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dolomite (as oxides)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lance</td>
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</tr>
</tbody>
</table>

First of all five mass balance equations of iron, carbon, CaO, MgO and Si are considered to estimate the five unknowns namely weights of steel, slag, lime dolomite, slag and volume of waste gas. It is followed by oxygen balance to calculate the volume of oxygen and heat balance to estimate the turndown temperature of liquid steel and slag. These balances are defined by following equations:

**Iron balance:**
\[
Wt_{hm}\times Fe_{hm}+wt_{ore}\times Fe_{O3 \_ ore}\times 112/160+wt_{scrap1}\times Fe_{scrap}+wt_{dri}\times (Fe_{dri}+FeO_{dri}\times 56/72 +Fe_{O3 \_ dri}\times 112/160) = wt_{steel}\times Fe_{steel} + wt_{slag}\times FeO_{slag}\times 56/72
\]
Silicon balance:
\[ Wt_{hm} \times Si_{hm} + wt_{ore} \times SiO_2_{ore} \times 28/60 + wt_{lime} \times SiO_2_{lime} \times 28/60 + wt_{scrap} \times Si_{scrap} = wt_{steel} \times Si_{steel} + wt_{slag} \times SiO_2_{slag} \times 28/60 \]

Carbon balance:
\[ Wt_{hm} \times C_{hm} + wt_{dri} \times C_{dri} + wt_{scrap} \times C_{scrap} = wt_{steel} \times C_{steel} + wt_{gas}/(%CO_2 \times 44/12 + %CO \times 28/12) \]

CaO balance:
\[ wt_{lime} \times CaO_{lime} + wt_{dolo} \times CaO_{dolo} = wt_{slag} \times CaO_{slag} \]

MgO balance:
\[ wt_{ore} \times MgO_{ore} + wt_{dolo} \times MgO_{dolo} + wt_{lime} \times MgO_{lime} = wt_{slag} \times MgO_{slag} \]

Oxygen balance:
\[ wt_{ore} \times (SiO_2_{ore} \times 32/60 + MnO_{ore} \times 16/71 + Fe_2O_3_{ore} \times 48/160 + MgO_{ore} \times 16/40) + wt_{dri} \times (FeO_{dri} \times 48/16 + Fe_2O_3_{dri} \times 48/160 + wt_{lime} \times (MgO_{lime} \times 16/56 + CaO_{lime} \times 16/56 + SiO_2_{lime} \times 32/60) + wt_{dolo} \times (MgO_{dolo} \times 16/56 + CaO_{dolo} \times 16/56 + SiO_2_{dolo} \times 32/60) + wt_{oxygen}(Lance) = wt_{slag} \times (SiO_2_{slag} \times 32/60 + FeO_{slag} \times 16/56 + P_2O_5_{slag} \times 80/142 + (MnO_{slag} \times 16/71 + CaO_{slag} \times 16/56 + MgO_{slag} \times 16/40) + wt_{gas}/(CO_{gas} \times 2800 + CO_2_{gas} \times 32/4400) \]

Heat Balance:
Heat balance is very much important for correct temperature predictions. The heat inputs and outputs are as following. The data corresponding to heat balance equations is given in Table 2.

### Table 2. Components of heat balance during BOF process

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensible Heat of Hot Metal, Scrap</td>
<td>Sensible Heat of Steel</td>
</tr>
<tr>
<td>Exothermic Heat of Reactions (at 25 °C)</td>
<td>Sensible Heat of Slag</td>
</tr>
<tr>
<td></td>
<td>Sensible Heat of Waste Gas</td>
</tr>
<tr>
<td></td>
<td>Endothermic Heat of Decomposition (at 25 °C)</td>
</tr>
<tr>
<td></td>
<td>Heat Losses</td>
</tr>
</tbody>
</table>

Heat Input:
The heat input is through sensible heat of hot metal, heat of reactions and endothermic heat of melting/decomposition.

**Sensible heat of Hot Metal:**
\[ heff \times wt_{hm}/100 \times (Fe_{hm} \times (0.72105 \times t_{hm} - 3.8665) + Si_{hm} \times (0.9614 \times t_{hm} + 1450.46) + Mn_{hm} \times (0.836 \times t_{hm} - 140.448) + C_{hm} \times (1.996786 \times t_{hm} - 1057.54) + P_{hm} \times (0.563 \times t_{hm} - 169.355)) \]

**Heat of Reactions:**
\[ heff \times wt_{slag}/100 \times (FeO_{slag} \times 3862.32 + SiO_2_{slag} \times 15160 + MnO_{slag} \times 5425.64 + P_2O_5_{slag} \times 10345.5) + wt_{gas}/100 \times (CO_{gas} \times 4898.96 + CO_2_{gas} \times 8930) \]

**Endothermic Heats of Decomposition:**
\[ heff \times wt_{ore}/(Fe_2O_3_{ore}/100) \times 5166.48 \]
Heat of Formation of Slag Compounds:
heff*(wt_slag/100)*(SiO2_slag*4493.5*28/60+P2O5_slag*11623.5*62/142)

Heat Output:
The heat goes out as sensible heat of steel, sensible heat of slag and sensible heat of waste gas. There is also some heat loss to the atmosphere. The calculation procedures are explained below.

Sensible Heat of Steel:
1/100*wt_steel*(Fe_steel*(0.72105*T_steel-3.8665)+Si_steel*(0.9614*T_steel+1450.46)+Mn_steel*(0.836*T_steel-140.48)+C_steel*(1.996786*T_steel-1057.54)+P_steel*(0.563*T_steel-169.355))

Sensible Heat of Slag:
1/100*wt_slag*(CaO_slag*(0.94886*T_steel-325.455)+SiO2_slag*(1.254*T_steel-530.86)+FeO_slag*(2.09*T_steel-2131.8)+MnO_slag*(0.8151*T_steel-326.87)+MgO_slag*(1.3376*T_steel-539.22)+P2O5_slag*(1.137*T_steel-119.548))

Sensible Heat of Off-Gas:
wt_gas/100*(CO_gas*(1.5884*T_steel-652.08)+CO2_gas*(1.2331*T_steel-449.496))

Phosphorous, Manganese and Sulphur prediction models:
The endpoint phosphorous, manganese and sulphur are predicted by thermodynamic derived equations. The manganese prediction is done by thermodynamics as follows:

\[ \ln(\text{MnO})/[\text{Mn}] = A/(T+273) + B. \ln(\text{C}_\text{Steel}) + D \]

The phosphorous is predicted using Healey’s equation which is as follows:

\[ \ln(\text{P2O5})/[P] = A/(T+273) + B. \ln(\text{Slag}_\text{Fe}) + C. (\text{CaO}) + D \]

The sulphur was evaluated using thermodynamics as follows:

\[ \ln(\text{S})/[\text{S}] = A.\text{Basicity} + B \]

The coefficients of these distribution equations are estimated by performing regression analysis with the plant data.
The static control model is developed in MATLAB [1] where inputs can be given to the model through interactive graphical user interface.

Calculation of closing item for heat balance: Heat losses for the converter during blowing and waiting:
The closing item of heat balance which is unaccounted heat loss from the converter during blowing and waiting time is estimated by considering heat losses through metallic shell of converter (via refractory lining), through lance cooling system and through mouth by radiation. A separate mathematical model has been developed for this purpose which takes care of converter dimensions, refractory thickness, water flow rate and differential temperature in lance cooling system.

**DYNAMIC CONTROL MODEL**
The dynamic model focuses on dynamic mass balances of oxygen, carbon and nitrogen in association with the waste gas information (volumetric flow rate and compositions). Dynamic control models have the capability to predict the state of the process (steel and slag compositions and weights, temperatures) at any intermediate time during the process. Most common models are based upon waste gas information where decarburization rates (d[C]/dt), iron content of the slag (FeO) can be calculated by performing dynamic carbon and oxygen balance during the process.

In the present work dynamic control mathematical model in conjunction with waste gas information has been developed. The kinetics of lime dissolution is taken as the function of FeO level in the slag. The model estimates transient carbon composition in the bath, d[C]/dt, bath temperature and slag composition (CaO, FeO and SiO2). The post-combustion ratio is also estimated at the mouth of the converter. Based upon all these calculations and coupled analysis of post-combustion ratio in association with the lance height, waste gas flow rate, lance oxygen flow rate and estimated FeO level of the slag, the behavior of slag formation and its nature (dry vs. foamy) can be predicted which helps to decide suitable strategy for smooth process control.

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Post Combustion control model:
The post-combustion ratio is given as ratio of %CO$_2$ to (%CO$_2$ + CO) inside the converter. The degree of combustion of CO to CO$_2$ depends on the waste gas entrainment in the oxygen jet, decarb urization in the hot spot region, and kinetics of reduction of FeO in the slag which depends on lance height and oxygen flow rate during the blow [2,3]. The schematic diagram exhibiting the mechanism during post-combustion is given in Figure 1 [2,3].

![Schematic diagram exhibiting the mechanism during post-combustion](image)

Figure 1. The schematic diagram exhibiting the mechanism during post-combustion [2,3]

The post-combustion model in BOF process in the present work is based upon the approach given by Hirai and his co-workers [3].

The theoretical post-combustion ratio is given as:

$$\alpha_c = 0.1\left(\frac{h}{d_0}\right)^{0.3} - \left(\frac{h}{d_0}\right)^{-0.7} + 0.01$$

Where \((h/d_0)\) is the ratio of effective lance height to throat diameter of lance \((d_0)\), which is calculated as:

$$\frac{h}{d_0} = \frac{L_G - H_c}{d_0}$$

Where \(L_G\) is the lance height and \(H_c\) is the calculated length of the supersonic core calculated as:

$$\frac{H_c}{d_0} = 4.12 p_o - 1.86$$

Where \(p_o\) is the upstream pressure of lance given by following expression:

$$F_{O_2} = \frac{\{1.414 \times 10^5 n d_0^2 p_o\}}{\sqrt{T_o}}$$
Where $F_{O2}$ is the oxygen volumetric flow rate, $n$ is the number of nozzles and $T_o$ is the upstream oxygen temperature.

The actual post-combustion ratio based upon online waste gas composition measured behind the cooling stack after deducting the effect of infiltrated air after the waste gas leaves the mouth of the converter which results in following expressions:

$$%CO = X + 2 \times \left( \frac{21}{79} \right) \left\{ 100 - (X + Y) \right\}$$

$$%CO_2 = Y - 2 \times \left( \frac{21}{79} \right) \left\{ 100 - (X + Y) \right\}$$

$$\alpha_m = \frac{\%CO_2}{\%CO_2 + \%CO}$$

Where $X$ and $Y$ are the waste gas CO and CO$_2$ percentages measured behind cooling stack. The relative post-combustion ratio ($Rel_{PCR}$) is calculated as:

$$Rel_{PCR} = \frac{\alpha_m}{\alpha_e}$$

**Post Combustion vs. slag formation vs. dry blow vs. slopping:**

Dry slag formation (opposite in nature to that of slopping) is the part of main blow period when the foam height constantly decreases with time, leading to eventually a situation of the metal droplets coming out from the mouth of vessel (spitting) and the rise in exhaust gas temperature. The consequences of dry blow are: (a) Lance skulling, mouth jam, hood jam, (b) Damage to the lining (in top cone), (c) Loss in thermal efficiency of the process since the rising gas and the circulating droplets with in the vessel are not able to mix with slag and then impart their heat to slag and leaving the vessel carrying all sensible heat.

The dry blow can be predicted by employing the post combustion model and operator can take corrective action in advance to avoid dry blow. During the period of dry slag formation there is a steady decrease in the post combustion value and $Rel_{PCR}$, depending upon the degree of dry slag formation. The waste gas flow rate and temperature also increases during dry blow. Therefore in practice, the occurrence of dry slag formation can be predicted by simultaneously observing these parameters and their trends and a corrective action can be taken by the operator much in advance.

**RESULTS AND DISCUSSION**

The static model developed in this work is validated with plant data. Out of one month heat data for a converter, only 200 data sets with complete information were filtered and used for calculations. MATLAB code for static model based upon heat and materials balance has been developed. The calculations were performed using static model for all filtered 200 data sets. The closing item for heat balance and oxygen balance are estimated using actual observations in such a way that predicted temperature and oxygen blown matches with the actual values. The scatter plots for predicted results vs. actual observations for lime and temperature are plotted in Figure 2. The predicted results are in good agreement with the industrial data. In Figure 3 the oxygen level in bath is plotted with respect to carbon in bath. The results are close to the equilibrium line showing that bottom stirring system is very much effective. The closing item of heat balance is calculated and it was found that heat loss during blow is directly proportional to the silicon level of the hot metal (Figure 4). Since the slag volume depends on silicon level so the heat loss is more because of more covered area on lance and refractory lining. The static model is further developed in the form of a graphical user interface where input parameters can be entered and output can also be displayed after calculation (Figure 5).
Figure 2. (a) Predicted vs. actual lime wt. (b) Predicted vs. actual bath temperature

Figure 3. The observed [C] vs. [O] in the bath

Figure 4. (a) The calculated heat loss during blow (b) The heat loss vs. silicon content of hot metal
The dynamic control model results based upon representative data of steel plant are shown in Figure 6-10. The post-combustion ratio, slag compositions (CaO, FeO and SiO₂), rate of decarburization in bath, rate of oxygen change in slag, basicity and bath composition (carbon and silicon) are calculated and plotted at different process moments. These results are observed in association with waste gas volumetric flow rate to predict the behavior of the slag and subsequent occurrence of dry blow/slopping. Based upon these observations, the dry blow period was predicted at 2500-4000 NM³ oxygen moments which is reflected by abrupt drop in post-combustion ratio and increase in waste gas flow rate (Figure 6). Simultaneously negative rate of oxygen change in slag, low FeO in the slag along with very high rate of decarburization in metal bath is also observed (Figure 7, 8). The lime dissolution rate is also observed to be retarded during the same period (Figure 9). The operator should have raised the lance height at 2500 NM³ oxygen moment in order to avoid the dry blow based upon all these observations. In this way the dynamic control model coupled with post-combustion model can be used to predict dry blow/slopping well in advance and corrective action can be taken by raising the lance height at appropriate moment.

Figure 6. Process moment vs. The actual PCR, relative PCR, waster gas flow rate and lance height

Dry blow period between 2500-4000 Oxygen moment. It is reflected by abrupt drop in PCR and increase in waste gas flow rate. The lance height should have been raised beyond 2500 Oxygen moment to avoid dry blow phase.
Figure 7. Process moment vs. rate of oxygen change in slag, decarburization rate in metal and FeO level of slag

Negative dO slag/dt due to FeO consumed in decarburization resulting in low FeO slag making it the solid and blow getting dry. It happened during 2500-4000 Oxygen moment.

Figure 8. Process moment vs. CaO, SiO2, FeO level of slag and slag weight

Abrupt drop in FeO level beyond 2500 NM3. The lance should have been raised to avoid this situation.
Static and Dynamic control model has been developed using industrial data of JSW Steel Plant. While developing static control model, proper selection of closing item of heat balance is very much important, this is found to have very strong relationship with Si content of hot metal. Calculation of heat loss during blowing/waiting by fundamental equation of heat transfer may give reasonable idea of values of closing items. Dynamic control model is developed using waste gas information which helps to predict dry blow/slopping well in advance by monitoring actual post combustion and relative post
combustion ratios in addition to waste gas flow rate at the converter mouth. Lime dissolution rate, basisity, FeO level, d[C]/dt and d(O)slag can also be predicted dynamically which can help further to predict the nature of slag in addition to dry blow prediction. Corrective action can be taken well in advance (like raising lance height when there is steep drop in post combustion and FeO content, rise in waste gas flow rate, Steep rise in d{C}/dt and prolonged negative values of d(O)slag/dt etc. The static and dynamic and post combustion based dynamic control model developed in this work can guide the process with smooth operation with minimum dry blow and slopping. The model is still under validation and will be implemented in JSW Steel Plant.

ACKNOWLEDGEMENTS

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REFERENCES
