Evaluation of Bottom Stirring System in BOF Steelmaking Vessel Using Cold Model Study and Thermodynamic Analysis

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Water model experiments have been carried out in a 1/6th scaled down model of the basic oxygen steelmaking (BOF) converter in order to optimize the bottom tuyere configuration of a new vessel bottom. The mixing time in the model was determined by conductivity measurement technique for ten different types of bottom tuyere configurations. Amongst the various bottom tuyere configurations, the one consisting of 8 tuyeres in a symmetric non-equiaugular position was found to be the best with respect to mixing in the vessel. The same bottom tuyere configuration of the new vessel bottom was compared with the previous bottom tuyere configuration (6 tuyeres), and about 40% improvement in the mixing in the bath was observed with the new bottom tuyere configuration. After determining the best bottom tuyere configuration from water model, it was implemented in the actual steelmaking vessel at the LD1 shop of Tata Steel. Average phosphorus partition ratio improved by 10 to 12 points, and the average %Fe$_{total}$ in the slag dropped by about 1–2%, and a record vessel life of more than 2 000 heats was achieved in the first campaign itself with the new bottom tuyere configuration. Thermodynamic evaluation of dephosphorization in the BOF for different bottom stirring systems adopted by Tata Steel over a period of several years has been carried out using plant data of several heats. Gradual improvement in the approach to equilibrium due to improvement in the bottom stirring systems has been observed.

KEY WORDS: basic oxygen steelmaking; bottom stirring; water model; mixing time; dephosphorization.

1. Introduction

Tata Steel adopted basic oxygen steelmaking in the year 1982 with the introduction of two basic oxygen steelmaking furnaces (BOF) fitted with top three hole lance (THL) at its LD1 shop. Mixing in the top blown BOF is inadequate in comparison to bottom and combined blown converters. Therefore, top blown BOFs were converted to combined blowing process in the year 1989–90 through the introduction of Bath Agitated Process (BAP). The additional stirring provided by the bottom agitation (BAP) prevented excessive oxidation and led to decreased oxygen content of the metal bath. Various other benefits viz., improved slag metal interaction, increased metal yield, better ferroalloys recovery etc. were realized due to switching over to the combined blowing process. All these advantages have been primarily attributed to improved hydrodynamics in the bath due to better mixing in the combined blown converter.$^{1,2}$ Subsequently, the top three hole lance (THL) was replaced with the six hole lance (SHL) in the year 1992 and the bottom blowing BAP process was changed over to the new technology of six straight bottom tuyeres in the year 1997 to further improve the hydrodynamics of the process. The difference between the BAP process and the new technology is that in the former case inert gas (argon) is injected into the vessel through porous canned refractory brick elements whereas, in the latter case six or eight straight pipes are used as bottom tuyeres for injecting inert gas into the vessel. Also, in the BAP process injected inert gas enters the bath in the bubbling regime whereas, in case of bottom tuyeres gas enters the bath in the jetting regime which, after a short distance disintegrates into swarm of bubbles.

Recently, size of the bottom portion of both the BOF vessels of LD1 shop has been increased. In the present work, position of the 8 bottom tuyeres in the new vessel bottom has been optimized and relocated using mixing time experiments in the water model. The best bottom tuyere configuration determined from the water model was subsequently implemented in the actual steelmaking vessel at the LD1 shop of Tata Steel. Average phosphorus partition ratio improved by 10 to 12 points, and the average %Fe$_{total}$ in the slag dropped by about 1–2%, and a record vessel life of more than 2 000 heats was achieved in the first campaign itself with the new bottom tuyere configuration. Thermodynamic evaluation of dephosphorization in the BOF for different bottom stirring systems adopted by Tata Steel over a period of several years has been carried out using plant data of several heats. Gradual improvement in the approach to equilibrium due to improvement in the bottom stirring systems has been observed.

2. Experimental

The study was carried out in a 1/6 scaled down model of BOF converter where all the linear dimensions of the model were scaled down by 1/6th of the actual dimension of converter. The old bottom of the model vessel was changed to larger size and various bottom tuyeres were fitted. The modified Froude number was employed to choose the appropriate dimensions of the top lance tip and the bottom tuyeres, and for selecting the appropriate blowing conditions.$^{2,4}$ The modified Froude number used for the model design is defined as:
\[ Fr_{No} = \frac{\rho_g u^2}{(\rho_\ell - \rho_g) g L} \] ...................(1)

Where \( u \) is velocity of gas, \( L \) is characteristic length, \( g \) is acceleration due to gravity, and \( \rho_g \) and \( \rho_\ell \) are density of gas and liquid respectively.

Details of the model parameters have been described elsewhere. Schematic diagram of the experimental setup is shown in Fig. 1. The model was fitted with six-hole top lance (SHL) similar to the one used in the actual BOF operation. Many different tuyeres configurations for the new bottom of the vessel were employed during mixing experiments in order to determine the best configuration. Some of the bottom tuyeres configurations are detailed in Table 1 and Fig. 2.

In the mixing time experiments, the model was filled with water up to a height of 200 mm simulating the usual bath height in the converter. Accordingly, appropriate lance height was chosen. The extent of mixing was determined by the measurement of conductivity of the water bath using aqueous solution of potassium chloride of strength 1.293 N as a tracer. A standard conductivity meter was used for the measurement of conductance of the solution. The final probe location for monitoring the conductance of water bath was selected after measurement of conductivity at several locations of the bath. Figure 3 shows a typical variation in the conductivity ratio with time for probe locations 1 and 3. The probe location point (Probe 1 in this case) showed the longest mixing time and it was considered to correspond to the bulk uniform mixing time of the water bath. Similar technique has been adopted by several other investigators for the determination of mixing time in the water model. Air was introduced through the top lance as well as from the bottom tuyeres at a predetermined rate. When the steady state was reached, a small quantity of tracer was injected and conductivity of the solution was recorded continuously with the help of a data acquisition system (DAS). The uniform mixing time was defined as the time after which the tracer concentration fell in and stayed within ±1.5% of the uniform concentration. Each experiment was repeated at least twice to ensure the reproducibility of the experimental measurements.

3. Results and Discussion

3.1. Mixing Study

Results of mixing experiments were plotted in terms of dimensionless relative mixing time and percentage bottom gas flow rate. Relative dimensionless mixing time has been defined as:

\[ t'_{\text{mix}} = \frac{t_{\text{mix}}}{t_{\text{mix, top blowing}}} \] .....................(2)

where \( t_{\text{mix}} \) is mixing time for the combined blown cases and \( t_{\text{mix, top blowing}} \) corresponds to mixing time in case of top blowing only. Lower is the relative mixing time, better is the mixing.

### Table 1. Details of various bottom tuyeres configurations used in the new vessel bottom.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Configuration No.</th>
<th>Number of tuyeres</th>
<th>Details of bottom tuyeres</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Location 1</td>
<td>08</td>
<td>Eight tuyeres as shown in Fig 2a. All tuyeres are equispaced.</td>
</tr>
<tr>
<td>2</td>
<td>Location 1a</td>
<td>08</td>
<td>Eight tuyeres as shown in Fig 2b. All tuyeres are not equispaced.</td>
</tr>
<tr>
<td>3</td>
<td>Location 2</td>
<td>08</td>
<td>Eight tuyeres as shown in Fig 2a. All tuyeres are equispaced.</td>
</tr>
<tr>
<td>4</td>
<td>Location 2a</td>
<td>08</td>
<td>Eight tuyeres as shown in Fig 2b. All tuyeres are not equispaced.</td>
</tr>
<tr>
<td>5</td>
<td>Location 3</td>
<td>08</td>
<td>Eight tuyeres as shown in Fig 2a. All tuyeres are equispaced.</td>
</tr>
<tr>
<td>6</td>
<td>Location 3a</td>
<td>08</td>
<td>Eight tuyeres as shown in Fig 2b. All tuyeres are not equispaced.</td>
</tr>
<tr>
<td>7</td>
<td>Location A</td>
<td>08</td>
<td>Eight tuyeres in two vertical positions as shown in Fig 2c</td>
</tr>
<tr>
<td>8</td>
<td>Location B</td>
<td>08</td>
<td>Eight tuyeres in two vertical positions as shown in Fig 2c</td>
</tr>
<tr>
<td>9</td>
<td>Location C</td>
<td>08</td>
<td>Eight tuyeres used: 6 tuyeres at one PCD and two tuyeres very close to the centre of the bottom as shown in Fig. 2d</td>
</tr>
<tr>
<td>10</td>
<td>Location D</td>
<td>08</td>
<td>Eight tuyeres used: 6 tuyeres at one PCD and two tuyeres very close to the centre of the bottom as shown in Fig. 2d</td>
</tr>
</tbody>
</table>
Relative dimensionless mixing time has been correlated to the mixing efficiency as follows:

\[
\text{Mixing efficiency} \propto \frac{1}{t_{mix}}
\]  

Clearly, the lower the relative mixing time, better is the mixing efficiency. Mixing time for the top blowing only for six hole lance was found to be 115 s with the old vessel model. The same value of mixing time was adopted for calculating the relative mixing time for the new bottom stirring system using Eq. (2).

3.2. Effect of Bottom Tuyere Locations on Mixing

As mentioned already, ten different bottom tuyere configurations (Table 1) were studied for mixing in the new vessel (SHL and 8 bottom tuyeres). The top gas flow rate, lance and bath heights were kept constant during experiments. Effect of bottom gas flow rate was studied at each bottom tuyere locations keeping other parameters constant. Out of the ten different bottom tuyere configurations studied, the bottom tuyeres locations 2, 2a and B (Fig. 2) were found to have lower relative mixing time as compared to other bottom tuyere configurations. Mixing results for all the bottom tuyere configurations at two different bottom gas flow rates have been summarized in Table 2 for the sake of comparison.

3.3. Old vs. New Bottom Tuyere Configuration of the Vessel

The old BOF converter had a conical bottom portion. It had six bottom tuyeres uniformly positioned at a particular pitch circle diameter (PCD). The model study was also carried out for the old vessel using a similar 1/6th scaled down water model. Figure 4 compares the mixing results of the old vessel (fitted with SHL and 6 bottom tuyeres) with the new vessel (SHL and 8 bottom tuyeres) having eight tuyeres at various bottom tuyere locations as discussed above. Percentage bottom flow rate (BFR) in the abscissa of Fig. 4 has been defined as:

\[
\%\text{BFR} = \frac{(\text{Bottom gas flow rate}) \times 100}{\text{Top gas flow rate}}
\]

It is evident from Fig. 4 that the relative mixing time for the old vessel with 6 bottom tuyeres was much higher as compared to the new vessel having bottom tuyeres configuration 2, 2a and B. About 20% improvement in mixing in the
A new vessel was obtained for tuyere positions 2 and B in comparison to the 6 bottom tuyeres in the old vessel. Amongst the various bottom tuyeres locations, location 2a was found to be the best in terms of mixing in the new vessel. Overall, 40% improvement in the bulk mixing was observed for the new bottom tuyere configuration 2a in comparison to 6 bottom tuyeres in the old vessel.

3.4. Comparison of Relative Mixing Time for Various Bottom Configurations

Over the last 20 years, Tata Steel has made several changes in top blowing as well as in the bottom stirring system. During this period, the top oxygen lance was changed from three hole to six hole. At the same time bottom stirring was changed from the Bath Agitated Process (BAP) with four elements to six bottom tuyeres and then to eight bottom tuyeres. About three years back the conical portion of the bottom of the old vessel was changed to cylindrical shape having a larger diameter as mentioned in Table 3.

Water model study was carried out for all the above stirring systems adopted by Tata Steel. Figure 5 shows variation of relative mixing time with bottom gas flow rate for different stirring systems. The experimental conditions for different bottom stirring systems mentioned in Fig. 5 are shown in Table 3. It can be seen from the figure that there was a consistent improvement in the mixing time with the change of gas injection systems.

As mentioned already, the relative mixing time was highest with the combined blowing system having three hole top lance and the BAP for gas injection through the bottom (Fig. 4). Whereas, in the new vessel (SHL and 8 bottom tuyeres) with larger bottom, eight tuyeres located at position 2a (non-equiaxial) gave the lowest mixing time. All other stirring systems such as: SHL+BAP and SHL+6 bottom tuyeres had mixing time in between the above two configurations i.e. between THL+BAP and SHL+8 bottom tuyeres (Fig. 5). It can be seen from the water model results that it was possible to lower the relative mixing time from about 0.85 with the THL+BAP to about 0.25–0.35 in the new vessel with the application of six hole lance and eight bottom tuyeres located at position 2a. The bottom tuyere configuration 2a was found to be the best in terms of mixing time and it was recommended for implementation in the BOF vessel in the plant.

3.5. Implementation of Optimum Tuyere Configuration in the Plant

Based on the mixing time studies the bottom tuyere configuration 2a was implemented in the vessel 1 of LD1 shop. Operating data of one full campaign were analyzed for this tuyere configuration and compared with the data of earlier SHL+6 bottom tuyeres stirring system. The average phosphorus partition index was plotted with respect to both average turndown temperature and average %Fe_{total} in the slag as shown in Figs. 6 and 7. In Figs. 6 and 7 the dephosphorization index has been defined as:

\[
\frac{\%P}{\%P}^{\text{index}} = c \cdot L_{p,\text{actual}} \cdot \frac{\%P}{c} \cdot L_{p,\text{actual}} \quad (5)
\]

Table 3. Experimental conditions for results shown in Fig. 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>THL-BAP</th>
<th>SHL-BAP</th>
<th>6 bottom tuyeres (old vessel)</th>
<th>8 bottom tuyeres (location 2) (new vessel)</th>
<th>8 bottom tuyeres (location 2a) (new vessel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top gas flow rate, lpm</td>
<td>930</td>
<td>1040</td>
<td>1040</td>
<td>1040</td>
<td>1040</td>
</tr>
<tr>
<td>Bath height, mm</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Lance height, mm</td>
<td>400</td>
<td>400</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Bottom tuyere size, mm</td>
<td>6.5</td>
<td>6.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Diameter of vessel bottom, mm</td>
<td>540</td>
<td>540</td>
<td>540</td>
<td>784</td>
<td>784</td>
</tr>
</tbody>
</table>
where \( c = \) a constant \((= 0.1)\) and \( L_{\text{F, actual}} = \frac{[\%P]_{\text{slag}}}{[\%P]_{\text{metal}}} \).

Figures 6 and 7 clearly show improvement in the dephosphorization of liquid steel with new 8 bottom tuyeres as compared to the old 6 bottom tuyeres. It can be seen from the figures that for the same average turndown temperature as well as average \( [\%\text{Fe}]_{\text{total}} \) in the slag, better phosphorus partition index was achieved with 8 bottom tuyeres as compared to 6 bottom tuyeres. The average phosphorus partition with 8 bottom tuyeres was found to be 10 to 12 points higher in comparison to 6 bottom tuyeres. Similarly, the average \( [\%\text{Fe}]_{\text{total}} \) in the slag with 8 bottom tuyeres was found to be about 1–2% lower in comparison to 6 bottom tuyeres. The campaign life of the vessel having dolomite lining was also increased due to this modification. A record vessel life of more than 2,000 heats was achieved within the first campaign of 8 bottom tuyeres at the LD1 shop.

3.6. Evaluation of Effectiveness of Bottom Stirring on Dephosphorization Efficiency

Recently, Choudhary et al.\(^\text{9}\) have carried out extensive thermodynamic evaluation of dephosphorization in the BOF vessel at Tata Steel. Amongst some of the well known correlation, Choudhary et al.\(^\text{9}\) found Turkdogan’s correlation\(^\text{10,11}\) to be the most reliable for predicting the equilibrium phosphorus partition \((L_p = \frac{[\%P]_{\text{slag}}}{[\%P]_{\text{metal}}})\) in the BOF vessel for Tata Steel’s practice. Therefore, in the present work the same procedure was adopted for the estimation of equilibrium phosphorous partition.

As stated already that after installation of 6-hole oxygen lance there has been modifications of bottom stirring arrangements. How has it helped in better dephosphorization? The scientific method of assessment of this is the closeness of attainment of equilibrium. The ratio \((L_p)_{\text{actual}}/(L_p)_{\text{equilibrium}}\) defined as approach to equilibrium \((R_p)\), is 1 if equilibrium is attained. Closer is this ratio to 1, more efficient is bottom stirring so far as dephosphorization is concerned. For quantitative assessment of this, the heat data were classified into the following sets.

Set 1: 8 non-equiangular bottom tuyere
Set 2: 6 equiangular bottom tuyere
Set 3: 4 element BAP

\( R_p \) was calculated for each individual heat. Gradual increase in the values of \( R_p \) from the BAP to the existing 8 non-equiangular bottom tuyeres system is evident from the Fig. 8. As the figure shows, average \( R_p \) increased from 0.3 with BAP to 0.52 \((i.e.\ 52\%)\) with existing 8 non-equiangular bottom tuyeres. This indicated that the modifications made over the years in the bottom stirring by various bottom stirring systems in the BOF vessel have contributed in bringing the actual \( L_p \) relatively closer to the equilibrium. In addition, it has been observed that improved stirring has also helped in reducing the average iron content of the slag from the initial 25% with 4 element BAP to about 19% with existing 8 bottom tuyeres besides minimizing the scatter in the plant data (Fig. 9). Attempts are under way on various fronts for gaining better understanding of the BOF process to further improve the dephosphorization control in the BOF converters at Tata Steel.

![Fig. 6. Variation of average phosphorus partition index with average turndown temperature for 6 and 8 bottom tuyeres.](image)

![Fig. 7. Variation of average phosphorus partition index with \( [\%\text{Fe}]_{\text{total}} \) in the slag for 6 and 8 bottom tuyeres.](image)

![Fig. 8. Improvement in average approach to equilibrium with different bottom stirring systems at LD-1 steelmaking shop.](image)

![Fig. 9. Total iron content of slag with different bottom stirring systems in the BOF vessel at LD-1 steelmaking shop.](image)
4. Conclusions

(1) Bottom tuyere configurations 2, 2a and B in the new vessel were found to give lower mixing index compared to other tuyere configurations studied.

(2) Bottom tuyere location 2a was found to be the best with respect to mixing amongst all the eight tuyere locations investigated.

(3) Phosphorus partition was improved by about 10 to 12 points with the new bottom tuyere configuration compared to earlier 6 bottom tuyere configuration.

(4) There has been gradual improvement in the approach to equilibrium from the initial 30% with BAP to above 50% with the present 8 non-equiaangular bottom tuyeres. In addition, total Fe content of the slag dropped from 25 to 19% with improved bottom stirring.

(5) Improved bottom stirring has led to an increase in the dolomite lining life of the vessel to more than 2,000 heats.

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