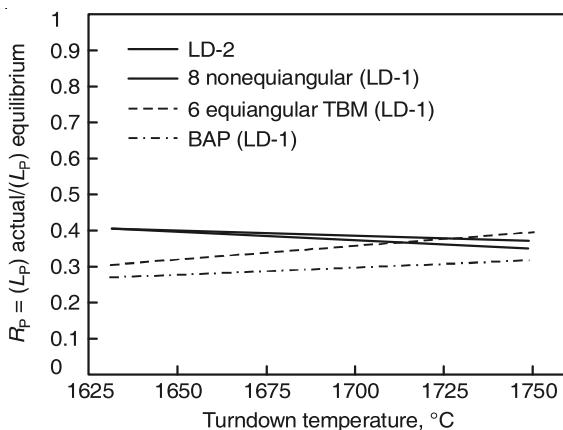
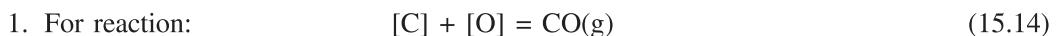


**Figure 17.16** Comparison of dephosphorisation characteristics in BOF steelmaking at Tata Steel with different bottom stirring arrangements, assuming 0% free lime in the slag (best fit lines).



**Figure 17.17** Comparison of dephosphorisation as in Figure 17.16 except that 10% free lime in slag assumed.

Turkdogan (1996) has attempted to find out some relationships for various reactions at converter turndown both for the bath agitated processes and OBM converters at US Steel Corporation. These are respectively known as BOF and Q-BOP at US Steel Corp. These are empirical relations and are related to some of the reactions discussed in Chapter 15, Section 15.4. Some of them are noted below as useful guides for quantitative estimates.



$$[\text{ppm O}] \sqrt{W_C} = 135 \pm 5, \text{ for BOF at } C \angle 0.05\% \quad (17.5)$$

$$= 80 \pm 5, \text{ for Q-BOP at } C \angle 0.08\%$$



$$(W_{FeO}) \sqrt{W_C} = 4.2 \pm 0.3, \text{ for BOF with C } \angle 0.1\% \quad (17.6)$$

$$= 2.6 \pm 0.3, \text{ for Q-BOP with C } \angle 0.1\%$$



$$\frac{[W_{Mn}]}{(W_{MnO})} \times \frac{1}{\sqrt{W_C}} = 0.1 \pm 0.02, \text{ for BOF with C } \angle 0.1\% \quad (17.7)$$

$$= 0.2 \pm 0.02, \text{ for Q-BOP with C } \angle 0.1\%$$

Comparison of performance on the basis of the above equations shows that at the same carbon content of molten steel, oxygen content of steel and FeO content of slag are lower for Q-BOP than those for the BOF at converter turndown. Manganese recovery into the metal is also higher in Q-BOP. These quantitatively demonstrate superiority of Q-BOP over BOF on the above parameters.

### EXAMPLE 17.2

For refining of steel in a bath agitated process, compare the statistical average plant data of  $[W_C] \times [W_O]$  before tapping, with the equilibrium value of the same for a tapping temperature of 1625°C.

**Solution:** From Section 17.7, statistical average value is  $20.5 \times 10^{-4}$ .

Equilibrium calculations can be done by using Eqs. (15.14) and (15.15) of Chapter 15, according to which:  $[W_C] \times [W_O]_{eq.} = p_{CO}/K_{CO}$ .

At 1625°C (i.e. 1898 K),  $K_{CO} = 411.3$ .

In Chapter 15, Section 15.4.3, the average pressure of gas bubble in steel bath was taken to be 1.5 atmosphere. Assuming that in bath agitated process, the bubble contains 50% CO and rest Ar or N<sub>2</sub>,  $p_{CO} = 0.75$  atmosphere.

Putting in values,  $[W_C] \times [W_O]_{eq.} = 18.2 \times 10^{-4}$ .

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# 18

## Process Control for Basic Oxygen Steelmaking

### 18.1 INTRODUCTION

Steel is made in the BOF process at a very fast rate and a key concern is, therefore, the exact determination of the blowing endpoint. Rapid changes in the temperature and chemical composition of the steel bath during oxygen blowing complicate predictions, and direct continuous measurements that are reliable are not possible in many cases even today. In conventional BOF steelmaking, the steel temperature and composition are measured at the end of the heat on the basis of steel samples withdrawn from the bath. This involves an interruption in the steel production process and a corrective oxygen re-blow is usually required leading to a loss in production and disruption in production scheduling. Today, process optimisation systems (Level 2) are available and can be applied to supervise and control BOF operations, starting from the ordering of hot metal and scrap to the alloying during tapping. Process tracking modules and the generations of set points are based on predefined production practices, and on the results from different process models that are activated according to the ongoing treatment phase. The required material quantities and compositions, the time when they are to be charged into the converter, as well as the exact volume of oxygen to be blown are calculated to produce a heat in accordance with the production plan, and which satisfies the specific steel grade requirements.

#### 18.1.1 Chronology of Developments

At the initial stages of BOF process development, the operator had to decide, before the start of the blow, how the oxygen blow would progress, what/when fluxes would be added during the blow, etc. to arrive at the desired endpoint in terms of temperature and composition. The entire ‘judgment’ was guided by previous experience, and hence involved a large amount of trial and error. After the blow was completed in the predetermined time, the oxygen lance would be withdrawn, the vessel tilted, and the final sampling and temperature measurements carried out

before tapping. During the blow, the vessel would have to be similarly tilted to check the actual progress of the blow, in terms of the prevailing bath temperature and composition at that instant of time. Corrections in temperature would be carried out by either making additions of iron ore or scrap to cool the bath, or heat it by further re-blowing, which would also be the method of adjusting the bath composition. The latter was more time consuming since chemical analysis of the samples by spectroscopy in a separate laboratory meant the loss of several minutes. Re-blows to adjust temperature/composition thus caused loss of production and had other adverse effects like lower lining life. Despite intermediate sampling/temperature check (s), often the temperature and/or the composition of the steel at the end of the blow would finish outside the desirable tolerance limits. This resulted in *off-grade heats*.

Following the advent of digital computers, it became possible to carry out fast quantitative calculations before/during the blow for a given set of endpoint conditions. Mathematical models were developed for calculating the initial charge mix, quantities of flux additions during the blow and the total oxygen that had to be blown. Such attempts were initially based exclusively on mass and heat balances. Later, further refinement became possible by incorporating statistically fitted process parameters, as well as slag–metal equilibrium relationships. A large variety of such mathematical models is in use in steel plants and is known as *Static Models*.

In such an approach, the aim is to make all the predictions before the commencement of the blow. How well it is followed during the progress of the blow is left to the operator and his judgement. This type of control is known as *Static Control*; the specific objective of which is to control the *endpoint* (*i.e.* at blow-end) temperature and carbon content of the bath. If it is carried out correctly, there is no need for further re-blowing or for any additions. Although other elements such as phosphorus, nitrogen, etc. are important, quantitywise they are very small, particularly in proportion to carbon. Therefore, elimination of carbon essentially determines the process time.

Static control by using computers improved the hit-rate of endpoint temperature and carbon significantly. As a result, static models have become an integral part of all basic oxygen steelmaking shops. How accurate an estimate such models can provide of the conditions of the bath at the end of the oxygen blow depends on the following factors:

- Accuracy of the model
- Accuracy of inputs to the computer system
- Consistency of steelmaking practices and quality of materials used
- Reliability of the sensors/measuring devices.

It needs to be emphasised that there are many variables which influence the rates of reactions in BOFs and some of these variables are difficult to control. Consequently, two heats with apparently identical inputs and blowing conditions may not finish with the same carbon and temperature. In scientific terminology, therefore, BOF steelmaking is a *Stochastic Process*. Some important sources of irreproducibility from heat-to-heat are:

- (a) Errors in weighing the charge and assessing the oxygen flow rate; for example, for a 300 tonne converter, it has been estimated that a small error in hot metal weighing can affect the final output appreciably:

| Error in<br>hot metal weighing | T, °C | Output errors |            |
|--------------------------------|-------|---------------|------------|
|                                |       | C, %          | Slag Fe, % |
| - 1 t                          | + 2   | - 0.003       | + 0.68     |
| + 1 t                          | - 0.9 | + 0.003       | - 0.61     |

- (b) Difference in the dissolution of lime owing to its reactivity, particle size, etc.
- (c) Dissolution of scrap on account of its size
- (d) Height and nature (including its structure) of the emulsion formed
- (e) Profile of the converter lining
- (f) Extent of mixing induced in the bath.

Out of the above, item (f), i.e. incomplete mixing, has been, by and large, eliminated by concurrent top and bottom gas blowing in BOFs. Mixing is not an issue in pure bottom-blown converters. However, the other sources of irreproducibility continue to exist to various extents, as a result of which, static control alone is not adequate. This has been demonstrated by data from many operating plants. Marked improvements in operation have been brought about by the utilisation of:

- Sub-lance
- Immersion-type carbon sensors
- Immersion-type oxygen sensors.

The sub-lance is an auxiliary lance adjoining the main oxygen lance assembly. No oxygen is blown through the sub-lance, but it is used to house various measurement probes—thermocouple, immersion carbon probe and oxygen probe—that are immersed into the bath from the top of the converter, while the vessel is still in a vertical position. Hence, the converter does not have to be tilted for making any measurements. The same set-up is used to withdraw samples from the bath for chemical analysis. The sub-lance is normally immersed 2 to 3 minutes before the predicted end of the blow. The data collected by the sub-lance probes are automatically fed into a computer, which compares the actual bath conditions with the model predictions to suggest further action to be taken by the operator. This is known as *Semi-Dynamic Control*. While static models by their very nature are not able to predict how to vary the blowing parameters (oxygen flow rate and lance height) with time and when to make additions during the blow, *Dynamic models* (which should not be confused with dynamic control) incorporate dynamic and kinetic features. As a result, the blowing parameters, additions, etc. are taken care of, resulting in better control of the endpoint conditions. Many modern BOF shops, therefore, have incorporated this facility.

The most sophisticated control system, known as *Dynamic Control* involves continuous waste gas analysis and flow rate measurement in order to determine the rate of decarburisation on a continuous basis during the entire blowing period. The information is fed back into a computer leading to continuous predictions and automatic oxygen blowing rate control, along with control of the bottom gas flow rate. This feature is in addition to sub-lance-based control.

Besides marked changes in the composition of the waste gas during the blow, there are variations in the noise level, extension of the outer lance pipe relative to the inner oxygen

carrying pipe, lance vibrations during the blow, etc. The intensity of these variations is influenced by the volume of the emulsion formed, the rate of decarburisation, slopping tendency, etc. Many modern converter shops use the trend in these variations as a means of controlling the entire blow; for example, sonic meters are used to gauge the extent and height of the slag–metal emulsion during the blow to get an idea of the rate of decarburisation and the amount of residual carbon in the bath along with the slag characteristics. The other methods can also provide similar information.

These are general features of the strategy and practice used for BOF process control, some specific details of which are given later. For general review, the book by Williams (1983) may be consulted.

## 18.2 MATHEMATICAL MODELS

### 18.2.1 Static Models

As stated in Section 18.1.1, static models are principally based on mass and heat balance of the process, taking only the initial and the final state of the system into consideration. Chapter 6, Sections 6.1 and 6.2 have outlined the basic procedure and equations for mass and heat balance exercises in connection with ironmaking in the blast furnace. Chapter 15, Section 15.2 has briefly covered the additional thermochemical features in connection with steelmaking reactions and their heat effects. Standard enthalpies of formation of some oxides along with the sensible heats of some materials have also been presented in a tabular form. These constitute the basis for formulating mass and heat balances in steelmaking processes and hence are not repeated.

Mass balances for Fe, O, C, CaO, MgO, etc. and heat balance yield several simultaneous linear equations, the solution of which requires a basis to be first selected. One metric ton (i.e. tonne) of steel is often taken as the basis. Inputs to the model have to be provided in the form of data and assumptions, such as:

1. Data: End-blow carbon and temperature, nominal heat size in tonnes, hot metal composition, quantity of scrap per tonne of steel, desired CaO/SiO<sub>2</sub> ratio in the slag, heat effects of the reactions, sensible heats as a function of temperature, etc.
2. Typical assumptions (not a complete list)
  - (i) % CO and CO<sub>2</sub> in the exit gas
  - (ii) exit gas temperature
  - (iii) temperature of slag and metal being the same at turndown
  - (iv) FeO and Fe<sub>2</sub>O<sub>3</sub> of the slag represented as total FeO
  - (v) constant heat loss rates
  - (vi) slag FeO and MgO contents, as a function of CaO/SiO<sub>2</sub> ratio, for good refining.

Turkdogan (1996) has provided some examples of calculations assuming that the sum of the four primary oxides CaO + MgO + FeO + SiO<sub>2</sub> is in the range of 88 to 92% of the slag weight (the rest being minor oxides). An empirical relationship between the CaO/SiO<sub>2</sub> ratio and the FeO, MgO contents of slag has also been assumed by Turkdogan.

On this basis it is possible to predict:

- Initial quantities of hot metal and scrap charges
- Flux and iron ore additions required during the blow
- Total quantity of oxygen to be blown.

Such predictions have been found to have some uncertainty owing to the simplifying assumptions made. In order to make the predictions more reliable, some terms are adjusted by statistical fitting of the model using a large number of actual data from previous heats. It has been claimed that, if the statistical analysis is properly adjusted along with additional inputs from the operators' know-how, i.e. by application of so-called *Expert Systems*, the accuracy of the predictions improve.

From physical chemistry principles it is possible to calculate the contents of phosphorus, sulphur, carbon, manganese and oxygen in the metal, which are in equilibrium with a given type of slag. Chapters 15 and 17 have presented some details of the various reactions and their application in the BOF. Using this approach, it is possible to predict the composition of the slag that would be present in the converter at turndown. This is necessary in order to arrive at the solute contents in the steel bath at the aimed turndown temperature. Modern versions of static models have also incorporated these in the computation programmes.

### EXAMPLE 18.1

Using the data and calculations of the BOF heat in Examples 15.1 and 15.2 of Chapter 15, carry out heat balance calculations to determine the temperature of liquid steel at the end of the blow. Make further assumptions as follows:

- (i) Basis of calculation: 1 tonne of steel as in Examples 15.1 and 15.2
- (ii) Reference temperature = 298 K
- (iii) Hot metal temperature =  $1275^{\circ}\text{C}$  = 1548 K; scrap, lime and oxygen inputs are at 298 K
- (iv) Final temperatures of liquid steel and slag are equal; also slag contains 2 wt%  $\text{P}_2\text{O}_5$
- (v) Heat loss by radiation, conduction and exit gas is 10% of the heat input.

**Solution:** Process heat balance calculations are long. They require extensive data and can be properly solved only by computer-oriented numerical method and iterative procedure. Therefore, many simplifying assumptions need to be made. Some have been listed already and the rest will be mentioned as they come.

From material balance calculations of Examples 15.1 and 15.2, it can be noted that per tonne of steel:

$$W_{\text{HM}} = 975 \text{ kg}, W_{\text{scrap}} = 97.5 \text{ kg}, W_{\text{slag}} = 130 \text{ kg}, \text{O}_2 \text{ required} = 41.7 \text{ Nm}^3$$

$$\text{Heat Balance: } \text{Heat Input} = \text{Heat Output} + \text{Heat Loss} \quad (\text{Ex. 18.1})$$

Sensible heat input by  $(\text{HM} + \text{scrap} + \text{CaO} + \text{O}_2) + \text{Heats of oxidation of (C + Si + Mn + Fe + P)}$  – Endothermic heats of melting of scrap and CaO = Sensible heats of liquid steel and slag at final temperature  $T$  + Heat loss. (Ex. 18.2)

Since heat loss is 10% of heat input, Eq. (Ex. 18.1) may be rewritten as:

$$0.9 \times \text{heat input} = \text{heat output} \quad (\text{Ex. 18.3})$$

Since, scrap, CaO and O<sub>2</sub> inputs are at 298 K, sensible heat input is only through hot metal. Table 15.2 gives some sensible heat data. Assuming that the sensible heat of HM is the same as liquid Fe,

$$\begin{aligned} \text{Sensible heat of HM} &= 975 \times (1/56) \times 10^3 \times [40.95T + 0.837 \times 10^{-3} T^2 - 2805] \text{ joules} \\ &= 109 \times 10^7 \text{ J} = 109 \times 10^4 \text{ kJ} \end{aligned}$$

$$\begin{aligned} \text{Sensible heat of liquid steel and slag} &= (1/56) \times 10^3 \times [1000(40.95T + 0.837 \times 10^{-3} T^2 - 2805) \\ &\quad + 130(48.85T + 2.26 \times 10^{-3} T^2 + 6.73 \times 10^5 T^{-1} - 16957)] \\ &= 843.8T + 20.2 \times 10^{-3} T^2 + 15.1 \times 10^5 T^{-1} - 8.945 \times 10^4 \text{ kJ} \end{aligned} \quad (\text{Ex. 18.4})$$

[Note: Sensible heat of slag has been assumed to be equal to that of CaO in the above equation]

Endothermic heats of melting = (1/56) {W<sub>scrap</sub> × 13807 + W<sub>CaO</sub> × 79534} = 12.37 × 10<sup>4</sup> kJ, where the values of heats of melting are in J/mol.

Exothermic heats of oxidation of elements

On the basis of Example 15.2, it is possible to calculate the number of kg·moles of elements oxidized (n<sub>i</sub>). Values of standard heats of formation of these oxides (ΔH<sub>f</sub><sup>0</sup>) are available in Table 15.1.

For C → CO reaction, n = (1000 × 0.033 × 0.9)/12 = 2.475 kg·mol.

Calculations for other reactions with similar procedure give 0.275, 0.348, 0.325, 0.044, 0.034 kg·mol for C → CO<sub>2</sub>, Si → SiO<sub>2</sub>, Fe → FeO, Mn → MnO, P → 1/2 P<sub>2</sub>O<sub>5</sub>.

$$\text{Total heat evolved} = \sum n_i \times (\Delta H_f^0)_i = 85.68 \times 10^4 \text{ kJ} \quad (\text{Ex. 18.5})$$

Estimation of final temperature (T) of steel and slag

$$0.9[109 + 85.68 - 12.37] \times 10^4 = 843.8T + 20.2 \times 10^{-3} T^2 + 15.1 \times 10^5 T^{-1} - 8.945 \times 10^4$$

As first approximation, ignore the T<sup>2</sup> and T<sup>-1</sup> terms. Then, from the above equation, T = 2046 K.

In the next approximation, including the T<sup>2</sup> term too, the trial and error solution gives T = 1960 K = 1687°C.

## 18.2.2 Dynamic Models

Static models can be used to calculate the optimum charge mix, requirement of additions during the blow, total oxygen required, time of blow, etc. They can be utilised for static control as well as semi-dynamic control taking the help of sub-lance measurements. However, by their very nature, static models are not able to predict variations in the blowing parameters (oxygen flow rate and lance height) as a function of time, as discussed earlier. For making such estimates, dynamic models are required.