

As Figure 17.6 shows, towards the end of the blow, the decarburisation rate decreases continuously and becomes almost zero. The emulsion collapses. It has been concluded that it happens below a *critical carbon concentration* in the bath (may be taken as 0.3 wt. % as an average), and mass transfer of carbon in the bath becomes rate controlling. Since,  $-d[W_C]/dt$  is proportional to  $[W_C]$  in such a situation, the rate becomes almost zero at very low carbon levels.

### EXAMPLE 17.1

Calculate the total interfacial area of metal droplets in the slag–metal emulsion at steady state (i.e. peak) decarburisation period of a BOF blow. Do the calculation for 1 tonne of liquid steel in the bath.

Assume:

- (i) The emulsion contains 7% of bath metal as droplets.
- (ii) The droplets of metal are spherical.
- (iii) The size distribution of the droplets are as follows.

Diameter ( $d$ ) , mm	0.2	1	2	5	10
Fraction of total number ( $N$ ) of droplets	0.05	0.2	0.5	0.2	0.05

(Note: Actually droplet size distribution is governed by probability; the above distribution data is for simplification.)

**Solution:** Per tonne of metal bath,

$$\begin{aligned}
 \text{Total mass of droplets} &= 1000 \times 0.07 = 70 \text{ kg} \\
 &= \rho_{\text{steel}} \times N \times \left( \frac{\pi}{6} \right) \times [0.05 \times 0.2^3 + 0.2 \times 1^3 + 0.5 \times 2^3 + 0.2 \\
 &\quad \times 5^3 + 0.05 \times 10^3] \times 10^{-9} \\
 &= 6.73 \times 10^3 \times N \times 41.5 \times 10^{-9} \text{ kg, since } 1 \text{ mm} = 10^{-3} \text{ m.}
 \end{aligned}$$

Calculations give  $N = 2.5 \times 10^5$ .

## 17.5 METALLURGICAL FEATURES OF BATH AGITATED PROCESSES

### 17.5.1 General

As mentioned in the Introduction (see Section 17.1), in the BOF process, the molten bath is not homogeneous with respect to composition and temperature owing to inadequate mixing, and it was found that simultaneous gas injection through the bottom tuyeres even at a low flow rate was capable of satisfactory bath homogenisation. It was also mentioned there that several commercial basic oxygen processes were developed by various steel companies around the world in the decade of 1970, all of which had provisions for some gas blowing through tuyeres/canned elements/porous plugs fitted at the bottom of the BOF vessels.

Better mixing and homogeneity in the bath offer the following advantages:

1. More reliable temperature measurement and sampling of metal and slag, and thus better process control
2. Less slopping, since non-homogeneity causes formation of regions with high supersaturation and consequent violent reactions and ejections
3. Faster dissolution of the scrap added into the metal bath
4. Better mixing and mass transfer in the metal bath with closer approach to equilibrium for [C]–[O]–CO reaction, and consequently, lower bath oxygen content at the same carbon content
5. Better slag–metal mixing and mass transfer and consequently, closer approach to slag–metal equilibrium, leading to:
  - lower FeO in slag and hence higher Fe yield
  - transfer of more phosphorus from the metal to the slag (i.e. better bath dephosphorisation)
  - transfer of more Mn from the slag to the metal, and thus better Mn recovery
  - lower nitrogen and hydrogen contents of the bath.

Items (4) and (5) above assume greater importance for end-point control of composition and temperature, since the emulsion collapses and bath stirring by CO evolution becomes less towards the end of the blow. Then, stirring from the bottom makes significant contribution towards enhancing the rates of reactions. In modern steelmaking practice, after the oxygen blow is stopped, the vessel is tilted for temperature measurement and sampling (this is known as *turndown* or *first turndown*). Then the vessel is made vertical again for about two minutes with only argon flow through the bottom tuyeres. This assists in further homogenisation and closer attainment of equilibria.

Chapter 4, Section 4.5 has briefly reviewed the relevant concepts of kinetics, mass transfer, mixing and *mixing time* ( $t_{\text{mix}}$ ). From there it may be noted that:

more stirring → more bath turbulence → faster mixing and mass transfer → lower  $t_{\text{mix}}$ .

In general,

$$t_{\text{mix}} = BP^{-m}f \text{ (geometry, vessel size)} \quad (4.63)$$

where  $P$  is specific stirring power.  $B$  and  $m$  are empirical constants. For a given vessel, therefore,

$$t_{\text{mix}} \propto P^{-m} \quad (17.2)$$

Since  $P$  is proportional to the bottom gas flow rate  $Q$ ,

$$t_{\text{mix}} \propto Q^{-m} \quad (17.3)$$

where  $m$  has been found to range between 1/3 and 1/2.

Figure 17.9 (Baker et al. 1980) shows the variation of  $t_{\text{mix}}$  with bottom gas flow rate per tonne of metal for several bath agitated processes. The results are in conformity with the variation expected from Eq. (17.3).

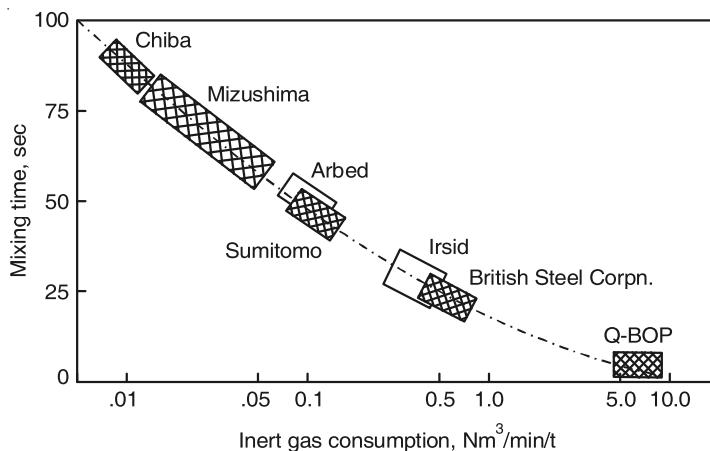


Figure 17.9 Mixing time as function of the bottom gas flow rate for some bath agitated processes.

### 17.5.2 Some Process Details

Baker et al. (1980), Tukkary and Tukkary (1998), Turkdogan (1996) as well as some others have reviewed the details of bath agitated processes. Here only a brief outline will be presented.

Table 17.1 (Turkdogan, 1996) lists the salient features of some of these processes. They differ in details of bottom blowing arrangements such as:

- Nature of the inert gas blown ( $N_2$ , Ar)
- Any other gases blown ( $O_2$ , air,  $CO_2$  and CO) along with inert gas
- Gas flow rate, number, and arrangement of the tuyeres
- Design of the tuyeres
- Programme of bottom gas injection during the oxygen blow period.

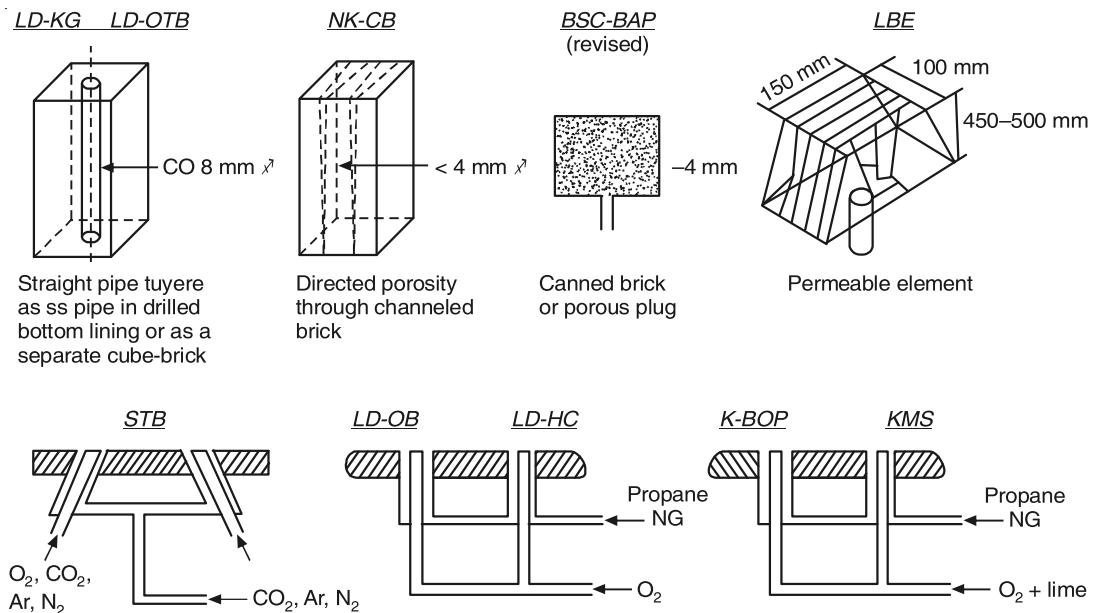
Table 17.1 Major bath agitated processes

Process	Developed by	Bottom gases injected	Flow rate, $Nm^3 \text{ min}^{-1} t^{-1}$
LBE	ARBED-IRSID (France)	$N_2$ , Ar	0.01–0.10
LD-CB	Nippon Steel Corp. (Japan)	$CO$ , $N_2$ , Ar	0.02–0.06
LD-KGC	Kawasaki Steel Corp. (Japan)	$CO$ , $N_2$ , Ar	0.01–0.20
LD-OTB	Kobe Steel Corp. (Japan)	$CO$ , $N_2$ , Ar	0.01–0.1
NK-CB	Nippon Kokan K.K (Japan)	$CO_2$ , $N_2$ , Ar	0.02–0.1

The most common choice are processes where only inert gas ( $N_2$ , Ar) are employed at volumetric flow rates equal to 2–4% of the oxygen flow rate through the top lance. Indian steel plants have also opted for such processes of combined blowing. The bottom gas is introduced through the bottom tuyeres, ranging in number from 6 to 16, depending on converter size, and

are generally arranged symmetrically around the central axis of the converter. Figure 17.10 shows some designs of the tuyere arrangements. In these processes, the operational features are similar to classical LD steelmaking as detailed in Chapter 16. The additional features include:

- Bottom gas flow schedule during oxygen blow
- Post stirring by argon after turndown.

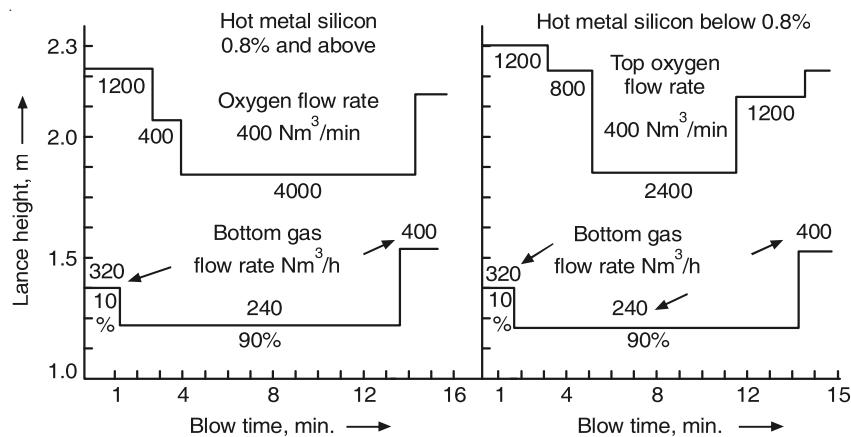


**Figure 17.10** Some designs of tuyere channels for bath agitated steelmaking processes (schematic).

Since argon is relatively expensive, nitrogen is used as much as possible. However, the use of nitrogen tends to increase the nitrogen content of steel, and this may adversely affect the eventual steel quality. During the initial stages, large-scale generation and evolution of CO has a flushing action because of which not much nitrogen is absorbed by the metal bath. However, towards the end of the blow, the flushing action is less. It is at this stage that argon has to be employed in the case of low nitrogen steels. Figure 17.11 (Tupkary and Tupkary, 1998) shows the blow profiles for the combined blown BOF vessel at Tata Steel for hot metal silicon below 0.8% and above 0.8%.

## 17.6 OXYGEN BOTTOM BLOWN PROCESSES

It has been already mentioned in Section 17.1 that in continental Europe, the bottom blown Thomas converters continued to be in use to refine high phosphorus hot metal even after the LD process was commercialised. Since air (containing over 80% nitrogen) was blown through the bottom tuyeres, the following major problems were encountered.



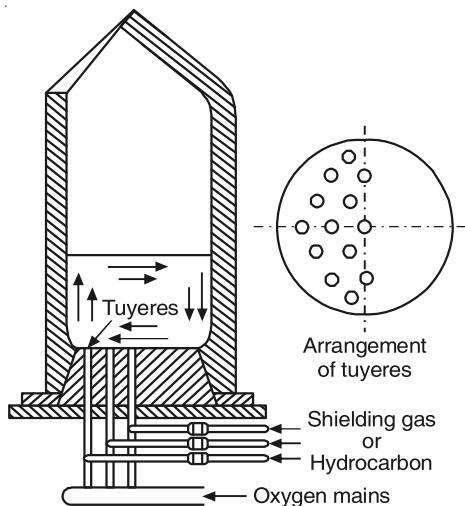
**Figure 17.11** Blow profiles of BAP vessel at Tata Steel using six-hole lance.

1. The steel contained inordinately high levels of dissolved nitrogen, which adversely affected the ductility, toughness and formability of the product.
2. Large volume of nitrogen in the converter exit gas resulted in considerable loss of heat. This adversely affected the thermal balance in the converter and did not allow the addition of large quantities of scrap.

Attempts were made to enrich the air with oxygen and raise its volume percent to as high as 40%. However, this had disastrous adverse effects on the bottom refractory life, requiring more frequent bottom repair/replacement. This occurred because the oxygen reacted with molten iron at the tuyere tip forming liquid FeO, which raised the local temperature. Liquid FeO is also very corrosive towards the refractory lining since it encourages the formation of low melting compounds. Both these factors contributed to bottom failure.

Finally, through collaborative R&D efforts essentially in Germany, a novel design of tuyeres was invented. It consisted of two co-axial stainless steel pipes, embedded in the magnesite bottom. Oxygen was blown through the central pipe and some hydrocarbon gas (such as propane) through the annular space between the inner and the outer pipe. The hydrocarbons decomposed into carbon and hydrogen as soon as they came in contact with molten metal. Since the process is endothermic, it cooled the region around the oxygen plume at the tuyere mouth, thus providing protection to the tuyeres and the refractory bottom. This is known as *thermal shielding*. Some local reduction of FeO by carbon and hydrogen provided additional protection resulting in decreased lining wear by corrosion/erosion phenomena. This is *chemical shielding*.

The process was first commissioned at the *Maximilianshutte* Iron and Steel Co., Germany in 1967, and hence, became known as the *OBM process* [Oxygen Bodenblasen (bottom blown) Maximilianshutte]. In France, the LWS process was invented in 1969 where liquid hydrocarbon was employed. Figure 17.12 shows the original OBM converter design along with its tuyere arrangements. Asymmetric layout of the bottom tuyeres as well as the converter conical top



**Figure 17.12** Original OBM converter and its tuyere arrangements, bath circulation indicated (schematic).

section made charging and tapping convenient, when the converter is tilted. The operation is similar to that of any normal LD, except that at end of the blow, nitrogen is bubbled through the tuyeres for a few minutes for final bath homogenisation and better approach to reaction equilibria.

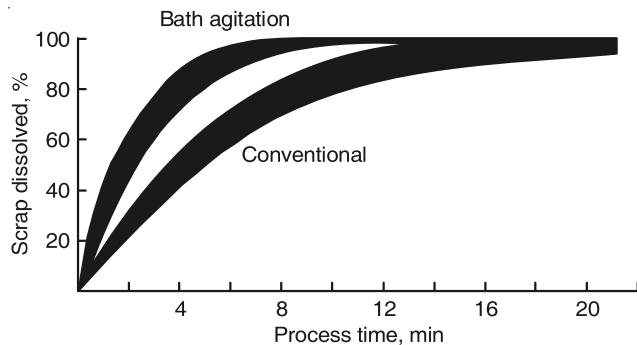
As noted in Section 17.5.1, bottom blowing gives several advantages that were confirmed when data from the OBM process were obtained. Therefore, this process generated worldwide interest even for refining low phosphorus hot metal. US Steel Corporation and some other companies installed OBM converters in their modernisation and expansion programmes. The traditional Thomas converter shops in Europe also switched over to OBM or LWS.

Although hydrocarbon shielding considerably improved the bottom life, it was still unsatisfactory compared with the LD process, where the life was much higher. Bottom maintenance with so many pipes was also problematic. On the other hand, the commercial hybrid refining processes developed in the decade of 1970s retained all the advantages of the LD process and brought in significant improvements in terms of better bath mixing. Hence, from the late 1970s/early 1980s, steel plants did not install any more bottom blown units and went for the bath agitated refining processes.

## 17.7 COMPARISON OF VARIOUS BASIC OXYGEN PROCESSES IN TERMS OF COMPOSITION CONTROL

The superiority of process control of bath agitated and oxygen bottom blown processes over straight LD is well-established. A large number of publications over the last 30 years provide evidence for the same. Here, performance of these processes with respect to control of steel composition will be very briefly demonstrated with the help of some examples.

Figure 17.13 (R. Baker et al. 1980) compares scrap dissolution rates with and without bath agitation. Agitation speeds up dissolution. Table 17.2 (Baker et al. 1980) compares some key



**Figure 17.13** Scrap dissolution rates with and without bath agitation.

**Table 17.2** Metallurgical parameters of some basic oxygen steelmaking processes (approximate values)

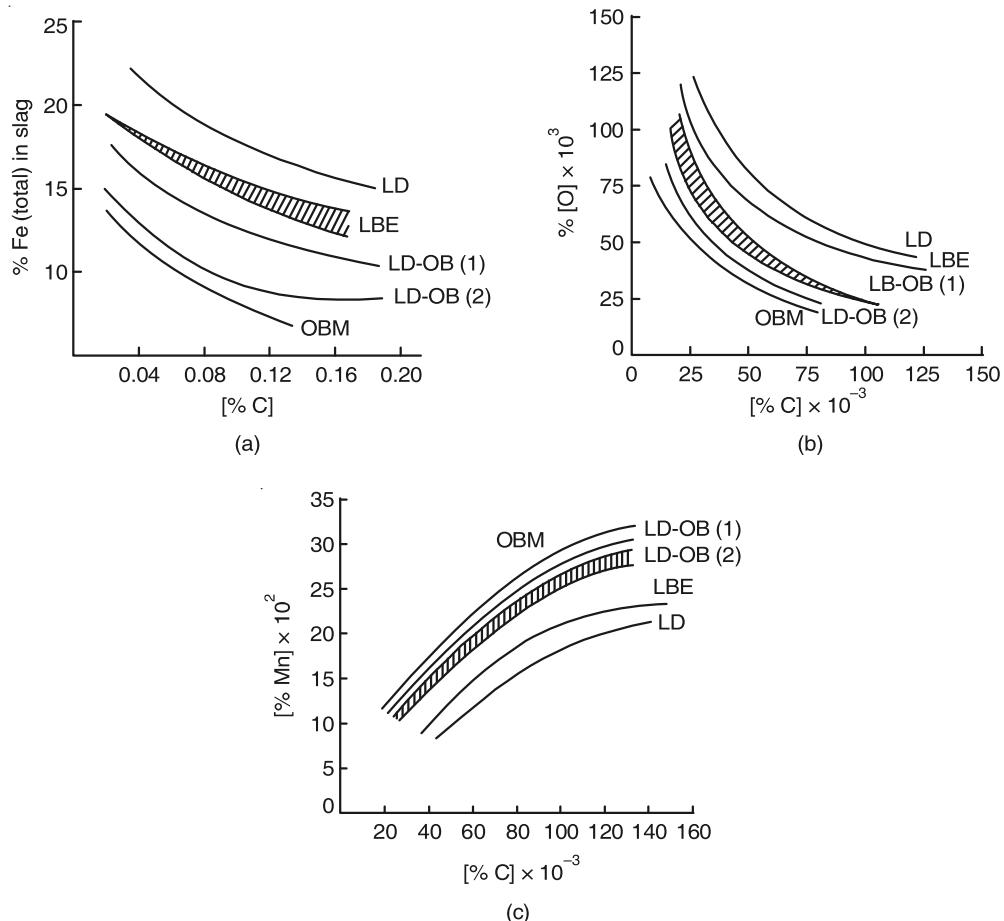
Parameter	LD	LBE	LD-OB	K-BOP	OBM
Bottom gas flow rate, $\text{Nm}^3 \text{ min}^{-1} \text{ t}^{-1}$	nil	0.01–0.1	0.1–0.5	1–1.5	up to 5.5
At 0.05% C turndown % $\text{Fe}_t$ in slag	20	18	14–15	13	10
% [O] in metal	0.06	0.05	0.04	0.04	0.03
% [Mn] in metal	0.14	0.18	0.21	0.22	0.3
(P)/[P]	70	80	80–90	110	120
Slopping	yes	minor	nil	nil	nil
Gain of yield of steel as % over LD	nil	+0.3	+0.4	+0.5	+0.7
Mixing time, seconds	100	50–75	30–35	10–30	10

metallurgical performance indices of LD, LBE and OBM processes. Figures 17.14(a), (b) and (c) also show this comparison regarding variation of Fe (total) in slag, pct. [O] and pct. [Mn] in bath as function of pct. [C] in bath.

It may be noted from Table 17.2 that out of the above, performance of the OBM is best, followed by LBE. Superior performance of LBE over LD is due to bottom gas stirring. So far as comparison of OBM with LBE is concerned, the explanation is more complex, since OBM differs from LBE in two major respects, given below.

- In OBM, bottom gas flow rate is much higher than that in LBE
- LBE uses Ar/N<sub>2</sub> as bottom gas, whereas OBM employs oxygen + hydrocarbon during blow, and then N<sub>2</sub> in post-blow.

Experiments at Hoogovens IJmuiden (Mink et al. 1993) have demonstrated beneficial effects of increasing bottom inert gas flow rate on metallurgical performance. These are demonstrated in Figure 17.15 (Mink et al. 1993) for Fe (total) in slag, Mn and P in metal. The figure shows percent changes of values over the practice with only top oxygen blow.

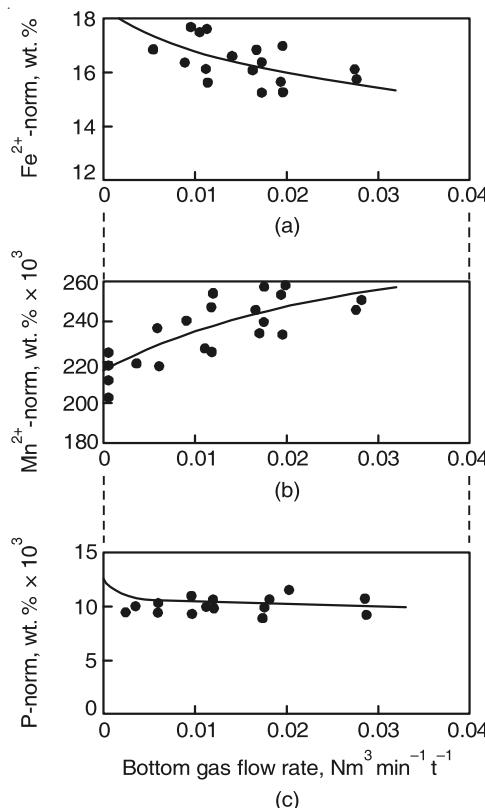


**Figure 17.14** Variation of Fe (total) in slag, [O] and [Mn] content of bath as function of bath carbon at turndown for some basic oxygen steelmaking processes.

Mink et al. obtained the following [C]–[O] relationship in molten steel before tapping from the furnace:

- Without bottom stirring,  $[W_C] \times [W_O] = 35 \times 10^4$
- With efficient bottom stirring,  $[W_C] \times [W_O] = 20.5 \times 10^{-4}$

At the LD-1 shop of Tata Steel, bottom stirring in converters was initiated in early 1980s by four symmetric tuyeres and later by six symmetric tuyeres. In the decade of 1990s, when LD-2 shop was commissioned, both LD-1 and LD-2 shops got fitted with eight symmetric tuyeres. Water model studies found decrease in mixing time with each of these changes. Thus eight bottom tuyeres had more efficient mixing than six tuyeres, and six tuyeres arrangement had more efficient mixing than four tuyeres.



**Figure 17.15** Variation of Fe (total) in slag, [O] and [Mn] contents of bath as a function of bottom inert gas flow rate.

Choudhary et al. (2005) evaluated phosphorus partition ( $L_P$ ) between slag and metal at converter turndown for large number of heats at Tata Steel for each tuyere arrangement. The ratio  $R_P$ , as defined below, was employed for assessment.

$$R_P = \frac{L_P}{L_P \text{ (at equilibrium)}} \quad (17.4)$$

It may be noted that  $R_P$  is a kinetic parameter.

At slag–metal phosphorus equilibrium,  $L_P = L_P \text{ (at equilibrium)}$ , and  $R_P = 1$ . If kinetic limitations do not allow attainment of equilibrium, then  $R_P$  is lower than 1.

Figures 17.16 and 17.17 (Choudhary et al. 2005) show  $R_P$  as function of turndown temperature for various tuyere arrangements. Since the turndown slag contains some undissolved lime particles and this is not determined in routine slag analysis data, two values of free lime, viz. 0% and 10%, were assumed. Figures 17.16 and 17.17 show that with better mixing by change of tuyere arrangements,  $R_P$  values increased, i.e. dephosphorisation was more efficient. These findings also are in conformity with evidences cited earlier.