LECTURE 13

Fundamentals of Converter Steelmaking Technology

Contents:

Key words: BOF steelmaking, jet penetration, refining reaction, soft and hard jet

Preamble

In converter steelmaking, oxygen at supersonic speed is blown on hot metal to remove the impurities like carbon, silicon, manganese, phosphorus. During the blow the lance distance is decreased to make the oxygen available into the bath for carbon removal. A three phase dispersion consisting of slag/metal droplets/gas bubbles forms during the blow. It takes around 15 to 20 minutes to blow the oxygen for refining. The tap to tap time varies in between 50 to 60 minutes depending upon oxygen flow rate, hot metal composition, lance profile and steel chemistry. It is interesting to note that the oxygen blowing time and the tap to tap time do not depend significantly on the converter capacity. This lecture attempts to discuss the fundamentals of converter steelmaking practice

Availability of oxygen

Oxygen is available energetically during the refining. The energetic availability of oxygen is obtained by passing a certain flow rate of oxygen through the nozzle as shown in figure 13.1

Figure 13.1(A):Convergent nozzle 13.1(B) Laval nozzle

In BOF steelmaking oxygen is blown through a laval nozzle. A Laval nozzle also called a convergent-divergent nozzle and is characterized by a flow passage whose cross sectional area decreases in the direction of flow and attains a minimum cross section area and then increases further in the direction of flow as shown in the figure 13.1(B). The minimum cross section area of the flow passage is called throat of the nozzle. The laval nozzle can accelerate the gas to the supersonic velocity The details of the design can be seen in the references given at the end of the lecture

Velocity of gas can be expressed in terms of Mach number

$$M = \frac{\text{velocity of gas}}{\text{velocity of sound}} = \frac{v}{a}$$

Thus at M= 1 gas exits the nozzle with the sonic velocity. Sonic velocity can be attained at the throat of the nozzle.

M<1 gas exits the nozzle at subsonic velocity

M>1 gas exits the nozzle at supersonic velocity.

Convergent nozzle can accelerate gas at $M \leq 1$

Convergent – Divergent nozzle can accelerate gas at M>1

In converter steelmaking Laval nozzles are used. Gas velocity at the exit corresponds to $M \approx 2$ to 2.4, flow rate of oxygen is $3\ \mathrm{Nm^3/min.ton}$ at pressures 10-14 bar. Multi –hole nozzles are used. Number of nozzles varies from 3 to 6.

Behaviour of free gas jet

First we will see the behaviour gas when it exits a single Laval nozzle in the surrounding which consists of air. A gas on exiting through a nozzle spreads in the surrounding and is called “free gas jet”, because spreading is not confined. Figure 13.2 show a free jet in the surrounding. It is characterized by the

Figure 13.2: Discharge of pressurized fluid stream through a Laval nozzle

potential (L_P) and supersonic (L_C) core length as shown in the figure. In the potential core no entrainment of the surrounding occurs and hence velocity of gas in both axial and radial direction is that at the exit value. Beyond the potential core both radial and axial velocity begins to decrease due to entertainment of the surrounding. Radial spreading of the jet can be seen in the figure. However a point Z_1 is reached in the free gas jet at which the gas velocity attains a sonic value (M=1). Within the length L_C gas velocity is above the supersonic value in both radial and axial direction. Beyond the supersonic core length the gas velocity is subsonic. Thus radial spreading and axial velocity decay beyond the potential core are the main characteristics of a free gas jet

Due to spreading mass of the jet increases which means that concentration of the gas at plane Z=0 decreases due to entrainment of the surrounding. If oxygen is flowing through the nozzle, concentration of oxygen at plane Z_2 is lower than at Z_1 and at Z=0. But mass of jet (jet consists of main fluid +

surrounding) at $Z_1 <$ mass at Z_2. Axial velocity of the jet is a function of axial distance measured from the nozzle exit.

One of the important property of the free jet is that it carries with it momentum flow rate which on hitting the liquid is converted into force and penetrates into the liquid. Momentum flow rate within the jet is conserved. This is an important property of the jet since it depends only on the upstream variables like pressure, number and diameter of the nozzle. It does not depend on the downstream conditions. For details see the references given at the end of this lecture

Behaviour of jets produced by multi-nozzles depends on number of nozzles and inclination angle (α) of each nozzle with the axis of the lance. Number of nozzles in converter steelmaking varies with the converter capacity but in general lay between 3 to 6. The inclination angle of each nozzle for a three hole, is $10-12^{\circ}$ and for five holes is 15 to 16° with the axis of the lance. (1)

Multi hole nozzles are compared with a single. The relationship between diameter of a single nozzle and the corresponding multi nozzles for the same flow rate of gas can be obtained from the area consideration in equation 2

A_1 = N x An 2)

From equation 2 it follows that

$$d_1 = \sqrt{N} \times d_n \qquad (3)$$

where d_1 is the diameter of a single nozzle and d_n is the diameter of each nozzle in a multi-nozzle and N is the number of nozzles.

The multi-free gas jets downstream the nozzle can coalesce or not would depend on inclination angle and number of nozzles for a given upstream pressure and flow rate of gas. A coalescing jet is similar to that of a single jet.

When angle of inclination is $10-12^{\circ}$ for a three hole lance, the multi-jets do not coalesce upto certain distance downstream the nozzle. A non-coalescing jet, when impinged on the liquid will produce penetration equal to number of jets.

The axial velocity decay and radial spreading depend on the ratio

$$\frac{\rho_{surr}}{\rho_j} = \frac{\text{density of surrounding}}{\text{density of jet}} \qquad (4)$$

If $\frac{\rho_{surr}}{\rho_j} < 1$ i.e. $\rho_j > \rho_{surr}$ jet is denser than the surrounding. Such a jet will spread slowly in the surrounding; how slow would depend on the value of $\frac{\rho_{surr}}{\rho_j}$. Accordingly jet velocity will decay slower at any distance downstream the surrounding. This situation could be, for example a cold jet is discharged in the hot surrounding. Length of the potential core, L_P and length of the supersonic core L_C will be longer than at $\frac{\rho_{surr}}{\rho_j} = 1$.

If $\frac{\rho_{surr}}{\rho_j} < 1$ jet is lighter than surrounding; jet spreads faster which results in lower L_P and L_C than $\frac{\rho_{surr}}{\rho_j} < 1$, for example cold jet is discharged into slag.

Action of free oxygen jet

Velocity of the free oxygen jet is important. Axial velocity decreases as the distance downstream the nozzle increases due to entrainment of the surrounding. In the converter as the blow begins, the surrounding of oxygen jet is hot atmosphere. As the blow continues the jet surrounding changes from carbon monoxide to slag. For most of the periods the jet is submerged into slag. The surrounding in the converter is dynamic. The velocity of the jet depends on upstream pressure, downstream axial distance and the surrounding. It is difficult to calculate the jet velocity when the surrounding is changing, but the momentum flow rate within the get is independent of the distance downstream the nozzle and can be calculated from:

$$\dot{m} = 1.029 \times 10^5 P_o N d_n^2 \left[\left\{1 - \left(\frac{P}{P_o}\right)^{0.286}\right\}\right]^{0.5} \qquad (5)$$

Where $\dot{\mathrm{m}}$ = momentum flow rate in (Newton)

P_o = upstream stagnation pressure (bar)

N= Number of nozzles

P = Surrounding pressure

d_n = Throat diameter of the nozzle(m)

Upstream stagnation pressure can be calculated

$$P_o(\mathrm{bar}) = 6.755(\mathrm{T})^{0.104} \qquad (6)$$

T= capacity in tons.

Throat diameter is function of converter capacity and number of nozzles

$$d_n = \frac{7.46}{\sqrt{\mathrm{N \ x\ 10^3}}}\ \mathrm{T}^{0.446} \qquad (7)$$

For a 150 ton converter, diameter of each nozzle of a 4 hole lance is calculated to be 0.035 m by equation 7. P_o is calculated to be 11.37 bar by equation 6 and total momentum flow rate produced by a four hole nozzle is 4057 N by equation 5. For more details the readers can look into the references given at the end of the lecture.

Jet carries with it momentum flow rate which on hitting the bath is converted into force. Thus action of free jet can be described in terms of dimensionless flow rate number (φ)

$$\varphi = \frac{\dot{m}}{\rho_l g\, x^3} \qquad (8)$$

ρ_l density of liquid $(\mathrm{Kg/m^3})$, g ($\mathrm{m/s^2}$) and X (m) is distance between the lance tip and liquid bath surface. If X is 3m and 1.5 m then $\varphi = 2.19 \times 10^{-3}$ and$= 0.0175$. We note that the dimensionless number increases with the decrease in the lance distance. Thus dimensionless flow rate number can be used to describe the dynamic variation of the lance distance. The dimensionless momentum flow rate number signifies the action of the gas jet on the bath at a distance X against the gravity

Jet penetrability

We calculate now the depth of penetration when the jet hits the bath surface at a distance x .Depth of penetration of an impinging jet (h) is

$$\mathrm{h(m)} = 4.407 \times (\varphi)^{0.66} \qquad 9)$$

At x = 3m, $\mathrm{h} = 0.23\ \mathrm{m}$ and increases to 0.46m when the distance x is decreased to 1.5m. This means that there will be shallow jet penetration in the bath at x=3 m, whereas at x=1.5m jet will penetrate deep into the bath.

Dimensionless flow rate number describes the effect of lance distance on the penetrability of jet.

Shallow jet penetration as obtained at higher lance distance is a “soft jet” as compared to deep penetrating jet as obtained at lower distance and is termed “hard jet”.

This would mean that a constant volume flow rate of oxygen supplied at constant pressure when discharged through a nozzle can be made to hit the bath “soft “and can be made progressively harder.

Thus method of oxygen supply in converter steelmaking practice i.e. through “free jet” is very effective in terms of physico- chemical reactions.

The effects induced by a reactive soft and hard jet impinging oxygen jet, when it hits the hot metal bath are given below.

Soft Jet	Hard Jet
• Oxidation of Fe • Shallow penetration • Slag/metal reaction • Slag formation is promoted. P removal is enhanced Too long duration of soft let will promote sloping of slag due to overoxidation	• O_2 available deep in bath • C oxidation is favoured. P removal is impaired • CO evolution occurs deep into bath and its escape through the bath agitates the bath • Droplets are produced which are then emulsified in the slag

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