A Review of Slag Splashing

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This review critically evaluates the factors affecting the process of slag splashing. Two mechanisms are involved in slag splashing, namely ‘slag wash coating’ and ‘slag ejection coating’. Our knowledge of slag splashing is largely based on physical modelling studies. It is necessary to optimise the following for good slag splashing:

(i) The characteristics of the nitrogen blow (Gas flow, Lance height, Lance angle, Slag depth); and
(ii) Slag composition.

It is important that the slag contains the right blend of low-melting and high-melting phases. The low-melting (FeO-rich) phases ensure good adhesion between the slag and refractory whereas the high-melting phases provide erosion resistance and a thermal barrier. Good slag properties are obtained with a FeO content of ca. 13% and MgO should be supersaturated (>8% MgO) to ensure that the slag is MgO-saturated rather than CaO-saturated so that high-melting MgO-Fe2O3 is formed rather than the low-melting calcium ferrites.

The factors affecting the uniformity of the slag-splashed layer are discussed.

KEY WORDS: slag splashing; slag washing; BOF; BOS; gas flow; lance height; FeO content; MgO content.

1. Introduction

The erosion of refractory linings of furnaces is a major cost in high temperature processes. Erosion occurs as a result of (i) chemical erosion due to attack of the refractory by the slag or the molten metal or (ii) thermal shock and mechanical wear due to the loading of scrap etc. into the vessel.

Slag splashing is one method used to produce a freeze lining. The Indiana Harbour Works of LTV were the first to initiate slag splashing practices in 1992 and this resulted in world records for the number of heats in contact with a furnace lining. Slag splashing has been adopted by other companies and Inland’s No. 4 BOF Shop obtained >60,000 heats from the furnace lining. Slag splashing was introduced in China in 1995 and is now used for >95% of steel produced by the BOF process in China.

1.1. Control of Refractory Lining Thickness

It has been reported that the maximum rate of erosion of the refractory lining in the vessel occurs during the initial and final blowing periods of the oxygen blow since the slag does not foam and provide some protection to the refracto-

ry.2) The erosion occurs as a result of oxidation of carbon in the brick with subsequent slag penetration into the refractory. The erosion rate increases with increasing temperature since (i) the slag has a greater fluidity (i.e. lower viscosity) and (ii) reaction rates increase with increasing temperature. The lining thickness should be uniform and should be 300–400 mm thick3,4); the thickness can be determined by laser imaging. Slag splashing protects the refractory and reduces refractory erosion. It has been suggested5) that the use of slag splashing alone is good enough up to 6,000 heats, but for >6,000 slag splashing should be used in conjunction with “gunning” of castable refractory to extend the life of the lining.

1.2. Slag Splashing Process

The slag splashing process was developed to extend the lifetimes and thereby reduce the cost of refractories in steel making vessels. The process was developed at LTV’s Indiana Harbor plant and has been introduced into various plants throughout the world. At the end of the BOS process the steel is drained to the ladle and molten slag is left in the bottom of the furnace. The oxygen-lance (used in the BOS process*) is lowered and a high-pressure nitrogen jet is used to splash the molten slag over the walls of the BOS vessel (Fig. 1) for a period of 2 to 4 min. This slag layer provides a consumable refractory lining which protects the furnace lining.6) The excess slag is then poured off to avoid build up of slag in the bottom (decreasing the volume of the
vessel) and the possibility of blockage of the tuyeres for vessels using combined blowing. The build up can be removed by oxygen blowing.

The chemistry and mineralogical nature of the end slag may have to be adjusted to obtain good slag splashing results. Compositional adjustment is usually focused on two components of the "end slag" viz. FeO and MgO concentrations. It was reported that best results were obtained when the slag was saturated with MgO and it may be beneficial to have an excess of MgO present in the slag to (i) obtain a high concentration of high-melting phases and (ii) increase the slag viscosity. To achieve this, magnetite or dolomite is added at an early stage of the nitrogen blow e.g. 10 s after the start to 30 s from the end of the blow. FeO tends to (i) reduce both the melting temperature of the slag and the viscosity of the slag and (ii) increases the amount of low-melting phases in the slag. Consequently, if the FeO content is too high, carbon is added (in form of MgO/50% C or MgO/30% C) to reduce the FeO content to a reasonable level. It has been suggested that the optimum FeO concentration is about 13% when casting low carbon steel grades.

Slag splashing is usually carried out with the vessel free of steel but can be carried out with steel and slag in the vessel providing that a different blowing practice is used. If all the steel is not removed before slag splashing, “skulling” of the vessel and lance can occur. Operational procedures for satisfactory slag splashing are given by Goodson et al. and Messina. Slag splashing practices have been developed for small vessels (25 tonne).

Good slag splashing requires:
(i) Optimisation of the parameters required to obtain a slag lining (e.g. gas flow, lance height, slag composition).
(ii) The creation of a slag lining providing sufficient protection of the refractory lining (which is dependent upon melting temperature, mineralogical constitution of the slag).

Wear rates are highest for the charge pad and trunnion areas and there is a tendency for slag accumulation in the region opposite the top hole due to slag ejected by the pneumatic stopper at the end of every tap.

The various factors affecting slag splashing are reviewed below.

2. Investigations of Slag Splashing Mechanisms

The mechanism of slag splashing has been largely studied by physical modelling. Both cold and hot models have been developed. These models make use of non-dimensional parameters to obtain quantitative relationships and have the advantage that they minimise the number of experiments to be carried out and remove the necessity for scaling factors.

2.1. Non-dimensional Parameters

The non-dimensional parameters used to represent the characteristics of the blow, slag properties etc. in slag splashing are given below. The various terms used to define lance height, etc. are shown in Fig. 2.

- Froude No., \( Fr \) is the ratio of inertial forces to gravitational forces and is used to represent lance blowing and bottom-blowing.

\[
Fr = \frac{\rho u^2}{gh} \frac{H}{H_r} \quad \text{(1)}
\]

where \( g \) = gravitational constant, \( h \) = lance height, \( u \) = gas velocity, \( \rho \) = density.

- Momentum No., \( Mm \) is the ratio of jet momentum and displaced liquid inertia

\[
Mm = \frac{\rho A n u^3}{\rho g x^3} \quad \text{(2)}
\]

where \( A_n \) = nozzle area and \( x \) = depth of cavity.

- Reynolds No., \( Re \) is used to compare flows leaving the nozzle.

Fig. 1. Schematic diagram showing slag splashing.

Fig. 2. Schematic diagram showing relevant dimensions in slag splashing.
\[ \text{Re} = d \cdot u \cdot \frac{\rho_g}{\eta_g} \] .................................(3)

where \( u \) is velocity at the nozzle exit.

- Weber No., \((\text{We})\) represents the ratio of momentum intensity to properties of the liquid and is used to characterise droplet generation, which involves both jet momentum and the properties of the liquid from which the drop is ejected.

\[ \text{We} = \rho_g u^2 / (\rho_l g \gamma)^{0.5} \] .................................(4)

- Morten No., \((\text{Mo})\) is a function of the properties

\[ \text{Mo} = g^{4/5} \gamma^{1/5} \rho_l \] .................................(5)

2.2. Physical Modelling Studies

The various studies are summarised in Table 1.

2.3. Slag Splashing Mechanisms

On the basis of physical modelling studies Peaslee\(^{31}\) pointed out that the coating of a furnace with slag is a complex process involving at least two mechanisms, viz. ‘slag wash coating’ and ‘slag ejection coating’ (Fig. 3).

2.3.1. Slag Wash Coating

This occurs as a result of the bulk movement of the slag causing the slag to rise above the nominal slag line (Fig. 4) and providing a coating of slag on the refractory.\(^{31}\) It is affected by various factors\(^{31}\): (i) Jet characteristics (momentum flow rate, lance height and angle, nozzles etc.), (ii) Slag properties (viscosity, density), and (iii) Geometry (slag aspect ratio, shape) and cavity and wave formation.

Peaslee\(^{31}\) showed in water-modelling studies that a standing wave is formed which can affect both washing and ejection mechanisms. In order to maximise the slag washing it is necessary to ensure that this standing wave approaches the lining walls.
2.3.2. Slag Ejection Coating

High velocity gas jets result in both agitation and the formation of crater. When the depth of the crater reaches a critical value slag droplets are ejected (Fig. 4). This is due to the high shear forces generated by the high velocity jet. The velocity and angle of the ejected slag is dependent upon the size and mass of the slag globules, velocity and trajectory angle and the gas flow (transfer) will be dependent upon the amount and location of the slag coating (and the heat (formation of crater). When the depth of the crater reaches a critical value slag droplets are ejected (Fig. 4). This is due to the high shear forces generated by the high velocity jet.

The balance of forces is given by:

\[ F_I = F_g + F_s \cos \beta \] ..................(6)

where \( \beta \) = angle between the gravitational vector and the horizontal, \( u \) = gas velocity, \( \gamma \) = surface tension of slag and \( p \) = density of slag and \( d_0 \) is the diameter of the droplet. The balance of forces is given by:

\[ 0.5 \pi d_0^3 \rho u^2 \left( \frac{u^2}{\gamma \cos \beta} \right) \cos \beta \] .............(7)

and the drop diameter can be derived by:

\[ d_d = \left( \frac{3}{8} \frac{u^2}{\gamma \cos \beta} \left( 1 - \left( 1 - \frac{\gamma g \cos \beta}{3 \rho u^2} \right) \right) \right) \] ...........(8)

3. Factors Affecting Refractory Life

The erosion of the refractory lining can be caused by a mixture of chemical corrosion and mechanical erosion. The latter can occur as a result of the impact of hot metal or scrap. Chemical corrosion of MgO/C refractories occurs in two steps:

(i) The oxidation of the carbon, and

(ii) Slag penetration through the pores left by the oxidation of the carbon and chemical attack of the MgO by the slag.

When the refractory lining is covered by a slag-splashed layer, erosion occurs by a different mechanism i.e. a mixture of (i) chemical dissolution of the slag splashed layer by the BOS slag and (ii) through partial melting of the slag layer as its temperature rises following the introduction of hot metal and the heat generated in the oxygen blow.

Zhou and Liu measured the erosion rate of MgO/C for slags in molten slags representing different parts of the oxygen blow (start, middle, end). They concluded that the starting slag composition did not cause rapid erosion but the impact of the hot metal could cause some erosion of the protective slag layer on the bottom of the vessel. In middle and final stages of blow, corrosion was found to occur by a mixture of chemical corrosion and high temperature melting. These findings do not agree well with the observation of Okhotskii and Schramko that rapid erosion occurred in both the start and final stages of the blow because foaming slags were not produced in these stages.

Tsai et al. measured the erosion rate in tests carried out in 2 stages:

(i) The surface of the specimens of MgO+14%C refractory was decarburised and then dipped in the molten slag for 30 min to form a 7 mm thick slag layer, and

(ii) The specimens were then heated in molten slag at 1 500°C and the lifetime of the specimen was determined from the time when CO was evolved i.e. the time required for the FeO in the slag to penetrate to the carbon in the refractory.

The lifetime of the coating was found to increase (i.e. erosion rates decreased) with:

(i) Decreasing temperature, and

(ii) Decreasing additions of FeO and Al₂O₃ and increasing additions of TiO₂, SiO₂ and MgO (slight).

The lower erosion rates obtained by adding SiO₂ may be due to greatly increased viscosity or alternatively, may be due to the formation of larger amounts of high-melting phases C₃S and C₆S.

Tsai et al. looked at the mechanism responsible for the protection provided by a (30 mm thick) slag layer with a melting temperature between 1 350°C and 1 400°C from molten steel at 1 650°C. They suggested the following:

(i) Low-melting phases (C₆F, CF, MF and the FeO₂-rich phases) form liquids at the hot face, and which then flow out of the slag layer.

(ii) The high-melting phases (C₃S, C₂S and the MgO-rich phases) remain and slow down the rate of erosion of the protective layer and provide thermal insulation.

(iii) The target is to ensure that the thickness of the pro-

![Fig. 5. Schematic diagram showing balance of inertial, gravitational and interfacial forces.](image-url)
3.1. Tapping Temperature

Tapping temperature \( T_{\text{tap}} \) is a measure of the temperature reached in the oxygen-blowing process. Thus where high-tapping temperatures are used there will be more melting and escape of the protective slag layer which will lead to shorter lifetimes for the lining.

Analysis of plant data when (see Fig. 6) using slag splashing procedures\(^{10,33}\) showed that refractory life \( n \) (no. of heats) was related to the tapping temperature \( T_{\text{tap}}, \degree \text{C} \) by:

\[
n = 208529 - 121T_{\text{tap}} \quad \text{........................(9)}
\]

Tapping temperatures tend to be higher in China \((\geq 1680 \degree \text{C})\) than in the USA \((1660 \degree \text{C})\)\(^{34}\) due to the steel grade, heat size and the lack of ladle metallurgy facilities in some Chinese steel shops.

3.2. Slag Viscosity

The rate of erosion of refractories (without slag splashing) is a linear function of the slag fluidity (reciprocal viscosity, \( \eta^{-1} \)). However, when using slag splashing the erosion of the protective slag layer will only be of importance in those areas where the liquid BOS slag is in contact with the protective slag layer. In these areas the slag viscosity could be important and erosion rates would be expected to decrease with (i) decreasing temperature (higher viscosity) and (ii) using slags supersaturated with MgO, since MgO particles present in the liquid will increase the viscosity significantly. However, in those areas where the slag layer is in contact with molten metal\(^{32}\) the principal mechanism of erosion will be the melting and leaching out of low-melting phases.

3.3. MgO Content of Slag

In processes where slag is in direct contact with refractory, the dissolution of the MgO lining by the slag is related to the difference in concentrations of MgO of the slag and that of the saturated slag \( (C_{\text{sat}} - C_{\text{slag}}) \). Consequently, the use of a slag close to MgO-saturation will reduce the driving force for dissolution and hence the erosion rate of the refractory. However, when using slag-splashed linings this mechanism will not benefit the lining life. The principal advantage of MgO additions to end-composition slags lies in the fact that it will increase the amount of high-melting phases and thereby possibly increase the thickness of the protective layer.

4. Effect of Blow Characteristics on Slag Splashing

The various operating factors affecting slag splashing are examined individually below.

4.1. Gas Flow Rate \( (Q_h, \text{m}^3 \text{s}^{-1}) \)

The amount of slag splashed by blowing \( (N_2) \) increases with increasing gas flow rate. This has been clearly demonstrated in water modelling\(^3 \) and laboratory simulation tests\(^31 \) and through the analysis of plant data.\(^30\) The effect of gas flow rate on two different slag compositions A and B (with C/S ratios of 3.6 and 2.5, respectively) was studied in terms of the splash height. The effect can be clearly seen in Fig. 7.\(^37\) Garg and Peaselee\(^15\) showed that an increase in gas flow rate resulted in an increase in slag deposition on all parts of the vessel. However, the increase was greater in the lower region than the upper region of the vessel. However, Tanaka and Okane\(^31\) reported that an increase in jet momentum resulted in an increase in splashing up to a maximum value beyond which it decreased due to the deeper penetration into the liquid slag.

Liu et al.\(^30\) reported that the parameter \( (H_d/D) \), (which represents the height of the nozzle above the slag line, multiplied by the aspect ratio of the furnace \( (H/D) \)), was a linear function (Eq. (4)) of the parameter\(^4 \) \( (Qh/d)^{0.33} \), which is effectively an adjusted flow rate, as shown in Fig. 8 where:

\[
(H_d/D) = 16.24 + 0.6(Qh/d)^{0.33} \quad \text{........(10)}\]

\[^{32}\text{This mechanism will also occur in areas where slag layer is in contact with molten slag.}\]

\[^{33}\text{Note that units of } (H_d/D) \text{ are m and } (Qh/d)^{0.33} \text{ are m}^3 \text{ min}^{-2}. \text{ However if the latter term is rewritten as } (Qh/d)^{0.33} \text{ the units become m, identical to that of } (H_d/D); \text{ this suggests there is a typographical error [29] in Eq. (10) and the y axis of Fig. 8.}\]
It should be noted that gas flow rates used in slag splashing may exceed normal demands and require the installation of booster compressors and high-pressure storage tanks. Detailed flow systems required to supply the necessary gas flow rates have been detailed by Snyder and Lach.

### 4.2. Lance Height ($h$)

Lance height can be defined with reference to either (i) the distance from the surface of the slag layer or ($h$ in Fig. 2) or (ii) the distance from the bottom of the vessel ($h + H_{\text{slag}}$ in Fig. 2). The lance height has a marked effect on the slag splashing process. The following observations have been made:

(i) Lance height affects the shape of the cavity and the wave (of slag) formed.

(ii) Decreasing the lance height results in a larger re-circulation zone in the cavity resulting in less slag washing and ejection.

(iii) Increasing the lance height ($h$) was found to increase the amount of slag splashed up to a maximum value beyond which it decreased as a result of increased penetration into the slag. An optimum lance height for good slag splashing has been reported as $h = 1.15$ m above bath surface and ($h + H_{\text{slag}}$) = 4.5 m above the bottom of the vessel. The optimum lance height is probably dependent on the size and shape of the vessel and the operating conditions.

(iv) Increasing the lance height of a jet (of constant momentum) decreased the amount of splash but the splash pattern moved radially-outward due to the change in the shape of the jet cavity. Increasing the lance height increased the mass flux of slag splashed in the lower region and decreased the mass flux in the upper sections of the vessel. This was due to the fact that increasing lance height resulted in the jet impact zone moving closer to the walls of the vessel thereby increasing the amount of slag hitting the lower regions and reducing the amount of splash hitting the top regions of the vessel.

Tong found slag splashed height was dependent upon jet penetration $h_{\text{opt}}/H_{\text{slag}}$, as shown in Fig. 10 and Liu et al. report an equation for calculating the amount of slag splashed as functions of these three variables.

Ciu et al. calculated the impact energy and penetration depth (through the slag), as functions of the lance height above the slag line ($h$), and the pressure of the gas. These workers also calculated the level of slag splashed in terms of the dimensionless parameter ($M_s/r_sD^3$) as a function of the dimensionless term ($h/D$) that relates the height of the lance above the slag, and the vessel diameter.

It can be seen from Fig. 11 that when the flow rate is increased, the lance height must be raised. The optimum lance level established in plant trials tended to be lower than those obtained in model experiments; the ratio ($h_{\text{opt}}/h_{\text{opt model}}$) had values of 0.90 ± 0.05. This was attributed to the fact the gas jet caused a decrease in slag temperature with a consequent increase in viscosity in the plant trials whereas it had no effect on the temperature in the model experiment.

Fabritius et al. studied combined blowing and found that the shape of the cavity is altered by the interaction of the lance jet with the plume. The cavity was found to become lower and without bottom blowing and resulted in the direction of splashing moving to lower trajectories.
4.3. Lance Characteristics

4.3.1. Number of Nozzles

Increasing the number of nozzles was found\(^{(15)}\) to have two effects:

(i) less slag was splashed in the central region of the nozzle, but
(ii) the slag splashing was more uniform.\(^{(15)}\)

The lower mass flux rates in the central region were due to the higher total jet energy impacting the slag volume which resulted in more cavities but of lower stability which, in turn, caused lower rates of slag splashing.\(^{(15)}\)

Liu \textit{et al.}\(^{(13,36)}\) reported that the amount of slag splashed was slightly lower for nozzles with secondary nozzles than for those with no secondary nozzles. Luomala \textit{et al.}\(^{(13)}\) found that plugging certain nozzle holes aided the selective splashing of slag.

4.3.2. Lance Angle

When the lance is inclined (through an angle, \(\alpha\) to the vertical) it can have the following effects:

(i) It generates greater shearing forces.\(^{(16)}\)
(ii) It alters the shape of the cavity and the wave formed.\(^{(31,42)}\)
(iii) It increases the amount of slag transferred by both slag washing and ejection mechanisms.\(^{(31)}\)
(iv) It reduces the vertical component of the velocity (impacting on the slag) but the increased horizontal component resulted in an increase in the slag hitting the side walls.\(^{(15)}\)

The reduction in vertical component resulted in less slag splashing in upper areas of the vessel but the increased horizontal component gave an overall increase in the amount of slag splashed.\(^{(15)}\)

Li\(^{(16)}\) reported that slag splashing was at a maximum when the angle, \(\alpha\) was 45\(^{\circ}\). Zhao Fengjun\(^{(7)}\) suggested that it may be possible to improve the uniformity of the slag splashed layer by increasing the number of holes and optimizing the angle of inclination.

4.3.3. Nozzle Design

It would appear that the exit angle of the nozzle has only a slight effect on the amount of slag splashed but may have some effect on the amount deposited in specific regions of the vessel. Liu \textit{et al.}\(^{(36)}\) found that the amount of slag splashed was greater for 12\(^{\circ}\) than for a 14.5\(^{\circ}\) nozzle angle.

Ha and Park\(^{(35)}\) found a slight increase in the slag splashed on the cone-part of the vessel when a small angle was used. Goodson \textit{et al.}\(^{(10)}\) reported the optimum nozzle design depended on the vessel. In their case a 12\(^{\circ}\) nozzle angle was the best since it deposited more slag in the upper vessel than the 14\(^{\circ}\) nozzle angle.

4.4. Bath/Slag Depth (\(H_{\text{slag}}\))

Increased bath depth results in a higher mass flux of slag in all regions since the slag has a shorter distance to travel.\(^{(15)}\) However, the slag flux was found to increase more in the central regions possibly due to more bulk movement.\(^{(15)}\) Ha and Park\(^{(35)}\) reported that the bath depth should exceed a certain critical value in order to obtain good slag splashing.

Liu \textit{et al.}\(^{(36)}\) used the non-dimensional parameter \(K = \text{mass of slag/mass of steel}\) to represent slag depth and reported that the optimum \(K\) values was 0.11 (or 11\%).

4.5. Size of Converter

Liu \textit{et al.}\(^{(30)}\) reported that numerical analysis of plant data showed that the required amount of slag splashing (\(Q_{\text{slag}}\)) (in tonnes) for satisfactory coverage was dependent upon the size (in tonnes) of the vessel (\(W\)). The relationship is given by Fig. 12:

\[
Q_{\text{slag}} = 0.301 W^n
\]

where \(n = 0.583\) to 0.650.

4.6. Superheat (\(\Delta T\))

The superheat (\(\Delta T\)) is defined as the difference between the tapping temperature \(T_{\text{tap}}\) (of the steel) and the liquidus temperature of the final slag \(T_{\text{liq}}\) i.e. \(\Delta T = T_{\text{tap}} - T_{\text{liq}}\). The superheat is important because it determines the thickness of the protective slag layer. Obviously a higher superheat will result in a thinner slag layer and faster melt-back of the protective slag layer.

Normally superheat is around 260\(^{\circ}\)C\(^{(34)}\) and usually the slag has good fluidity if \(\Delta T > 200^{\circ}\)C but if \(\Delta T > 300^{\circ}\)C then dolomite must be charged to cool the slag and increase the amount of high-melting phases present in the slag splashed layer.

4.7. Bottom Stirring

Bottom stirring produces a slight increase in the amount
of slag splashed providing the lance height \((h)\) exceeds a certain critical value. The following relation was reported:

\[
Q_{\text{slag}} = \frac{\rho_{\text{ slag}} \cdot (g \cdot m^2 \cdot s^{-1})}{H^2} = -2.005 + 3.202Q_B - 0.156Q_B^2 \\
-0.093Q_Bh + 7 \times 10^{-4} + 0.627h + 0.0011h^2
\]

Where \(Q_B\) is the bottom stirring gas flow rate \((Nm^3 \cdot h^{-1})\) and \(h\) is in mm.

Luomala et al.\(^{13}\) found that bottom stirring increased the amount of slag splashed but was also helpful in selective slag splashing of certain areas (e.g. charge pad, trunnion regions). Fabritius et al.\(^{29}\) found that the interaction of the plume with the cavity caused a lowering of the cavity and resulted in charges to the direction of the trajectory of the slag splash.

5. Effect of Slag Properties on Slag Splashing

It has been mentioned above that the slag should contain both high-melting and low-melting components for slag splashing to be successful. This has been referred to as “fractional melting”.\(^{43,44}\) A satisfactory slag contains two phases (i) a low-melting phase which tends to run away down the walls (and into ports) (ii) a high-melting phase which provides the necessary protection for the refractories. The low-melting phases tends to be rich in FeO phase and contains most of the S present. The high-melting phases tends to contain about 10–15% FeO (in the form of calcium ferrite, CaO·Fe₂O₃) an enhanced MgO content and a CaO/SiO₂ ratio of 2.5.\(^{43}\) Once the slag adheres to the interface it reacts with the MgO to form a high melting phase. A low-melting binder forms with MgO·Fe₂O₃ and Mg·Fe spinel phases.

The various factors affecting the performances of slags for slag splashing are considered below.

5.1. Liquidus Temperature \((T_{\text{liq}})\)

The liquidus temperature of the slag is important in several ways:

(i) The protective slag layer should contain enough high-melting phase to prevent attack of the furnace lining by the slag during the BOS process,

(ii) During the BOS process the low-melting phases tend to melt and flow out of the slag layer and thereby reduce the effective thickness of the slag,

(iii) During splashing a slag globule should not solidify during its trajectory since this could affect the adhesion of the slag to the interface, and

(iv) If the liquidus temperature is too high, the slag is not distributed uniformly and there is a tendency for the slag to build up the bottom of the vessel.\(^{26}\)

Thus it is apparent that good slag splashing is achieved when there is a good balance between the high-melting and low-melting phases.

Melting temperatures are usually reported as:

- Liquidus temperatures \((T_{\text{liq}})\) when they are measured by techniques such as differential thermal analysis (DTA) or hot thermocouple methods.
- Hemispherical temperature \((T_{\text{hem}})\) refers to the temperature where a pressed cylinder of slag attains a hemispherical profile (it has been argued that the test can be improved by not removing metallic iron from the slag layer before pressing\(^{45}\)). The reduction in height has been used to obtain a measure of the melting range of the slag where \(R=1-(H_T-H_0)\) where \(H_0\) and \(H_T\) are the initial height of the cylinder and the height at temperature \((T)\), respectively.\(^{34}\) Usually \((T_{\text{liq}}-T_{\text{hem}}) = +60 \pm 10°C\).\(^{43}\)

5.2. Effect of Different Slag Components on \(T_{\text{hem}}\)

The effect of different slag components on \(T_{\text{hem}}\) are shown in Figs. 13–15:

(i) FeO additions were found to cause a sharp decrease in \(T_{\text{hem}}\) for FeO contents of 0–15% but reduced \(T_{\text{hem}}\) by ca. \(-5°C (\%FeO)^{-1}\) for FeO contents in the range 15–30%.\(^{33,34,43}\) The melting range, (as represented by the height reduction of the slag) was found to be increased when the FeO content was <15%\(^{44}\) (Fig. 16).

(ii) TiO² additions were found to increase \(T_{\text{hem}}\) by ca. \(+5°C (\%TiO²)^{-1}\) for TiO² in the range (0–6%)\(^{33}\) (Fig. 13).

(iii) MgO additions have been reported to (i) bring about
an increase of ca. +1°C (%MgO)$^{-1}$ in $T_{\text{hem}}$ for MgO contents of 9 to 17%$^{33}$ (Fig. 13) and (ii) to cause a minimum in $T_{\text{liq}}$ at 8–9% MgO and then increase at ca. +10°C (%MgO)$^{-1}$.$^{30,43}$ (Fig. 15).

(iv) $\text{Al}_2\text{O}_3$ additions cause a decrease in $T_{\text{hem}}$ of about $-5^\circ\text{C}$ (%$\text{Al}_2\text{O}_3)^{-1}$ for contents in the (2–6% $\text{Al}_2\text{O}_3$) range.$^{33}$ and

(v) The $T_{\text{hem}}$ of slags with SiO$_2$ contents of 8 to 14% showed a general decrease in $T_{\text{hem}}$ with increasing SiO$_2$ content but appeared to be at a minimum around 13% SiO$_2$ (Fig. 13).

The effect of basicity ratio ($\text{CaO}/\text{SiO}_2$) i.e. ($\text{C}/\text{S}$) for a slag with 20% Fe content shows that the melting temperature increases with increasing ($\text{C}/\text{S}$) ratios when MgO >8% (Fig. 13).

5.3. Phase and Mineralogical Constitution of the Slag

For good slag splashing a balance of high- and low-melting phases is needed:

(i) The high-melting phase provides the thermal insulation and the main protection against refractory attack, and

(ii) The low-melting phase helps the slag to bond with the refractory and acts as a binder.

However, the FeO-rich liquid does tend to:

(i) React with the C in refractory lining to form a foaming slag$^{43}$ which then reacts with the MgO to form a dense, MgO-rich phase with MgO·Fe$_2$O$_3$ and Mg·Fe spinel which acting as binders$^{46}$ and

(ii) Melt and drain away during the oxygen blow; this liquid slag aids the dissolution of CaO and the rapid formation of a basic slag during the BOS process.

• High melting phases are: 3CaO·SiO$_2$ (or C$_3$S); C$_3$S; MgO-rich phase and magnesium ferrite, MgO·Fe$_2$O$_3$ (or MF).

• Low-melting phases are: Calcium ferrites, CF (mp 1216°C) and C$_2$F (mp 1440°C).$^{33}$

The RO phase has been reported to be a low-melting phase$^{33}$ whereas for slag with a high (>30%) FeO content it was considered to be a high-melting phase$^{49}$:

(i) Fractional melting tests showed that the high-melting phase compared with the original slag was richer in MgO and usually SiO$_2$ but contained less FeO (11%±2% total Fe) and S and there was little change in CaO$^{45}$ content,

(ii) The fraction of high-melting phases, C$_3$S and C$_2$S increased as (i) FeO content of the slag decreased and (ii) the SiO$_2$ content increased,$^{33}$

(iii) As the TiO$_2$ increases, the fraction of low-melting phase increases; Tsai et al.$^{33}$ found that TiO$_2$ tended to be associated with low-melting CF and C$_2$F phases,

(iv) MgO additions (MgO >8%) help to ensure that the
slags MgO-saturated rather than CaO-saturated (see Fig. 17) and thereby promote the formation of a high-melting phase (mp > 2023 K) formed from reaction between MgO and MgO·Fe₂O₃ instead of the low-melting CaO·Fe₂O₃, and

(v) As can be seen from Table 2 there are some differences in mineralogical constitution between the end slag and slag layer.37

5.4. Viscosity (η)

5.4.1. Effect of Viscosity on Slag Splashing

Several investigators have reported that the amount of slag splashed increases as the viscosity of the slag decreases.15,26,31,47 The viscosity of the slag has been reported to have an effect on:

(i) The relative amounts of slag transferred by ‘slag washing’ and ‘slag ejection’ mechanisms31 since a lower viscosity liquid will result in more bulk movement and less-stable cavities31 which result, in turn, in an increased number of slag ‘fingers’ and increased slag splashing;

(ii) Higher forces are required to break-up more viscous liquids and this leads to an overall reduction in slag splashing but especially so for the central regions near the jet.15

(iii) Slags with lower viscosity will tend to flow down the walls more rapidly6,26 and

(iv) “Dry” slags (2-phase) do not adhere well to the walls.6

Liu et al.36 reported the following relation between the mass of slag splashed per unit area, A, and the kinematic viscosity (v = η/ρ)

\[ A = \frac{2.415 + 0.356 \nu - 4 \times 10^{-4} \nu^2 - 0.645h}{+8.8 \times 10^{-6} h^2 - 7.1 \times 10^{-3} \nu h} \] ................................(12)

With the following units, \( \nu = 10^{-6} \text{ m}^2 \text{s}^{-1} \), \( h \) in mm (=10⁻³ m).

5.4.2. Factors Affecting Slag Viscosity

The principal factors resulting in an increase in slag viscosity are:

(i) Slag composition (especially a decrease in FeO content),

(ii) A decrease in temperature since viscosity is very temperature-dependent and the gas jet may result in considerable cooling, and

(iii) The presence of solid phases (e.g. excess MgO or high-melting phases like C₃S) which result in a large increase in viscosity and non-Newtonian behaviour. If the molten slag contains solid phases and consequently has a much higher viscosity than that calculated for the liquid (e.g. using models available for estimating slag viscosities from chemical composition48). It is also interesting to note that the physical modelling studies have been carried out with liquids and not with 2-phase materials which probably occur in slag splashing.

5.5. Density (ρ)

The amount of slag splashed has been reported to decrease with increasing density.34,47 It is interesting to note that the Momentum No. (ratio of jet momentum/displaced liquid inertia) and the Weber No. (ratio of momentum intensity/properties of liquid) used to characterise droplet generation are dependent upon \((1/\rho)\) and \((1/\rho^2)\) respectively. The principal factor affecting the densities of slags is the composition; densities of molten slags can be estimated by49:

\[ \rho = 2.460 + 18(\% \text{FeO}) \] .............(13)

Densities will increase slightly with decreasing temperature.

5.6. Surface Tension (γ) and Contact Angle

Increased surface tension has been found to result in a decrease in the amount of slag splashing.26,47 The dimensionless Weber and Morton numbers frequently used to model droplet generation are dependent upon the surface tension as \((1/\gamma)^{0.5}\) and \((1/\gamma)^{3}\) respectively. It has been reported26 from cold modelling experiments that the surface tension affects droplet size; the droplets were found to be finer with low surface tension (paraffin) and larger for a high surface tension (ZnCl₂ solution). Surface tensions of slags decrease with increasing concentrations of FeO and SiO₂.

6. Characteristics of the Slag-splashed Layer

6.1. Uniformity of Slag Layer

Ideally the protective slag layer should be deposited uniformly over the vessel walls. Xiao et al.53 examined three areas (1 = area around trunnions; 2 = bottom and 3 = other regions) of the converter. It was found that from 2000 heats onwards the thickness of the protective layer remained reasonably uniform with thickness of ca. 300, ca. 400 and ca. 500 mm, for areas 1, 2 and 3 respectively.

Grag and Peaslee15 looked at factors affecting the mass flux in various regions of the vessel. These were denoted as shown in Table 3 which indicates the following:

(i) A thicker coating to the lower regions can be achieved by increasing flow rate or decreasing the viscosity,

(ii) A thicker coating in the top regions can most usefully be obtained by decreasing the lance height since it results in a more uniform coating, and

(iii) A thicker coating in the trunnion area can be ob-

Table 2. Constitution of slags before and after slag splashing.

| Slag | C/S (%) | FeO (%) | MgO (%) | C₃S | C₄S | C₃F | RO | MgO |
|------|---------|---------|---------|-----|-----|-----|----|-----|
| A    | 3.6     | 18      | 5.6     | 20-30(20-30)| 40 (40) | 10-18(10-12)| 5-7(5-7) | (6-8) |
| B    | 2.5     | 25      | 4.4     | 60 (40-50) | 10 (15-20) | 5 (15-18) | 25 (3)    | (6)  |
tained by increasing the number of nozzles.

He suggested that build-up of the slag on the bottom of converter can be overcome by mixed (top and bottom) blowing. Luomala et al. found that selective slag splashing on the charge pad and trunnion region and reduced slag splashing in the region opposite the top hole could be achieved by a combination of bottom blowing and plugging up specific holes in the nozzle.

6.2. Heat Transfer across the Slag Layer

Cui et al. studied heat transfer at different sites in a slag-splashed lining and calculated the temperature at different times and locations during the BOS process when operating with a slag-splashed lining (Fig. 18). As can be seen from the figure the slag layer will experience temperatures of \(T > 123\) \(^\circ\)K during the oxygen blow. Even after 4 min the temperature will be sufficient to cause some flowing out of low-melting phases such as calcium ferrite (CF).

Joubert developed a model for the heat transfer of freeze linings.

6.3. Adhesion of Slag to Refractory

Little is known about the adhesion mechanism. It might be expected that:

(i) the slag would be non-wetting (\(\theta > 90^\circ\)) to carbon (and hence MgO+C) surfaces and would not adhere well to carbon-rich surfaces, and

(ii) the slag would wet MgO (\(\theta < 90^\circ\)) (and hence de-carburised MgO-refractory) and thus would infiltrate into the pores created by the oxidation of the graphite. This slag penetration would help to “key in” the slag layer.

Thus it would appear that the FeO-rich, low-melting phases are important to the adhesion process since they react with the carbon (to give a foamy slag). The subsequent removal of the carbon allows the slag to wet the MgO particles and to penetrate into the pores created by the oxidation of the carbon.

Mahapatra et al. found that slag adhered better to used MgO-C refractory plates than to new refractory plates. These observations are consistent with the findings above since slag would not adhere well to a carburized surface but would adhere well to a used surface where some decarburization has taken place.

Examination of refractories has shown that there are three layers:

(i) a protective slag-splashed layer,

(ii) a MgO layer (i.e. the refractory), and

(iii) a yellow layer, caused by the infiltration of a FeO-rich slag (and alkali sulphates) through the pores of the refractory which reacts with MgO to form MF and CF and C\(_2\)F in the slag will also react to form MF.

Since at high temperatures reactivity is usually associated with good wetting, the reactivity of the FeO with MgO should ensure good wetting of the slag (and hence good adhesion) to the MgO matrix. Tong et al. suggest that optimisation of the FeO\(_x\) content is important in slag splashing.

6.4. Optimum Slag Composition

It has been pointed out above that it is necessary to get the right mixture of low-melting and high-melting phases to get good slag splashing. This can be achieved by ensuring that (i) the FeO content is reduced below 13\(\%\) and (ii) ensuring that the slag is supersaturated with MgO. This is particularly important when the tapping temperature is high (1700\(^\circ\)C) since it is necessary to ensure that there is enough high-melting phase present to protect the lining during the BOS processing. The FeO content can be reduced by additions of MgO/C. The importance of the FeO content in the slag is underlined by the observations of the slag condition in terms of the Oxygen (O) content of the steel (i) \(Q > 900\) ppm the slag is too fluid (ii) \(Q = 400–900\) ppm, the slag is “too dry” and (iii) 400 ppm is excellent. The MgO is important since it ties up the Fe\(_2\)O\(_3\) to form high melting MF rather than the low-melting calcium ferrites. When slag splashing has been carried out on slags with up to 30\% FeO the MgO additions were found to be beneficial since they promoted the formation of high-melting phases.

One consequence of the high MgO content is that if the BOS slag contains a high MgO content, a slightly higher

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**Table 3.** Effect of an increase in various parameters on the amount of slag splashed; ↑ = an increase; ↓ = a decrease; the number of arrows indicates the magnitude of the effect on the amount of slag splashed, each arrow indicates an order of magnitude change to the lowest value (↑ or ↓).

| Parameter       | Top  | Centre | Bottom | Side  | Overall |
|-----------------|------|--------|--------|-------|---------|
| Lance height    | ↓    | ↑↑     | ↑↑↑    | ↑     | ↑↑      |
| Angle           | ↓    | ↓↓     | ↑↑↑    | ↑     | ↑↑      |
| Gas flow        | ↑↑   | ↑↑     | ↑↑↑    | ↑↑    | ↑↑      |
| No of nozzles   | ↓    | ↓↓     | ↓↓     | ↑     | ↓       |
| Slag Viscosity  | ↓    | ↓↓     | ↓↓↓    | ↓↓↓   | ↓↓↓     |
| Slag Depth      | ↑↑   | ↑↑     | ↑↑↑    | ↑     | ↑↑      |

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**Fig. 18.** Temperature distributions in the slag layer at different times in the blow.
C/S ratio is required for good de-phosphorisation.\textsuperscript{10} Slags with a high (CaO/SiO\textsubscript{2}) ratio (ca. 4) did not give “fractional melting” and in these cases it may be advisable to add SiO\textsubscript{2} during the slag splashing.\textsuperscript{11}

Small concentrations of TiO\textsubscript{2} have been reported to have an adverse effect on slag splashing which is probably associated with the fact that TiO\textsubscript{2} appears to be associated with low-melting phases.\textsuperscript{33}

7. Problems

7.1. Lance Skulling

This is particularly severe if some metal is left in the vessel during slag splashing.\textsuperscript{6} Skulling appears to be related to the heat transfer since it is not a problem when:
(i) The lance has sufficient water-cooling,\textsuperscript{22} and
(ii) A cold lance is substituted for the lance used in the oxygen blow.\textsuperscript{6}
Consequently, Xiao \textit{et al.}\textsuperscript{5} and Zhao\textsuperscript{7} both recommend the use of a different lance for slag splashing but which is very similar to the one used in the O\textsubscript{2} blow. It has been suggested that a rough (lance) surface is a pre-requisite for skulling to occur since it allows the slag to key onto the lance. The skull should not be left in the converter.\textsuperscript{7}

7.2. Skulling in the Vessel’s Mouth

Goodson \textit{et al.}\textsuperscript{10} point out the removal of slag skulls around the mouth of the vessel (caused by pouring off slag) is essential for long lining life. It can be removed by oxygen blowing but it is essential to use the correct lance height since if lance is too low there trunnions will be worn rapidly.

7.3. Blockage of Tuyeres

In bottom-blown converters the blockage of the tuyeres can be avoided by increasing the gas pressure and flow rate through the tuyeres.\textsuperscript{50} Xiao \textit{et al.}\textsuperscript{5} found that the end C content of the steel was higher when the tuyeres were blocked (Fig. 19) and found a flow rate of 350 m\textsuperscript{3} h\textsuperscript{-1} was sufficient (Fig. 21) since a flow rate of 700 m\textsuperscript{3} h\textsuperscript{-1} gave no improvement. They suggest\textsuperscript{50} that the product of %C and %O should have a value <0.003 for good BOS practice. It can be seen from Fig. 20 that this value corresponds to a slag thickness of ca. 120 mm. Xiao \textit{et al.}\textsuperscript{5} pointed out that for bottom-blown converters it is necessary to take the permeability of the slag (in the bottom regions of the vessel) into account as well as thickness of the slag layer for slag thickness needed for refractory protection. Consequently, it is essential to adjust the pressure in the bottom to get the required permeability ($P_{\text{permeability}}$)\textsuperscript{5}.

7.4. Effect on Sensors to Detect Metal/Slag

Sensors are embedded in the refractories to detect the presence of slag during tapping. The slag splashed layer interferes with the detection. Alternative procedures have been established for the detection of slag.\textsuperscript{51}

7.5. Effects of TiO\textsubscript{2}

It has been reported the presence of about 2% TiO\textsubscript{2}\textsuperscript{44} in the end slag has a deleterious effect on slag splashing. It has been suggested that TiO\textsubscript{2} additions reduce the viscosity significantly.\textsuperscript{33} Consequently, viscosity calculations were performed by the authors using the modified Iida model,\textsuperscript{48} which has proved to be very reliable for calculating slag viscosities. These calculations showed that the addition of 2% TiO\textsubscript{2} has little or no effect on the viscosity at 1,400°C.

A more likely reason is that the TiO\textsubscript{2} affects the melting characteristics of the slag. Additions of TiO\textsubscript{2} were found to increase the hemispherical temperature\textsuperscript{33} and hence would be expected to increase the amount of high-melting (protective) phases in the slag layer. However, plant experience suggests the opposite. The most likely explanation is that TiO\textsubscript{2} is associated with the formation of low-melting phases\textsuperscript{33} and thereby increases the amount of low-melting phases at the expense of the high-melting phases.

7.6. Effect of V\textsubscript{2}O\textsubscript{5}

V\textsubscript{2}O\textsubscript{5} reduces the melting temperature of the slag.\textsuperscript{52,53}

8. Benefits of Slag Splashing

8.1. Benefits to the Steelmaking Process

The principal benefits of slag splashing to the steelmaking process are:

\textsuperscript{44} Arising from illmenite additions to the blast furnace slag.
8.2. Economic Benefits

The principal costs associated with slag splashing are:

(i) Much longer refractory lives for furnace linings (over 60 000 heats at ISPAT Inland’s No. 4 BOF shop),
(ii) The use of a slag composition close to MgO saturation reduces the corrosion of the MgO lining,
(iii) Yield improvement arising from an increase in volume of the vessel with a consequent decrease in “slopping”,
(iv) Less CaO is needed in the BOS process due to the dissolution of the basic slag coating,
(v) The melting of the low-melting phases (e.g. CF) of the slag lining exists in the rapid formation of a basic slag and the rapid dissolution of CaO (from slag coating) by SiO2 in BOS slag which leads to more rapid de-phosphorisation,
(vi) More recycling of BOS slag, and
(vii) There are no significant differences in the S, P, Mn and N contents of the metal when slag splashing is applied and the product [%C][O] has a similar to that for combined blowing with slag splashing to that without slag splashing.

The costs of nitrogen refractories and labour vary significantly in various parts of the world. Slag splashing has been found to provide savings of 1.5 US dollars per tonne in the USA and 0.7 US dollars in China.

Savings in refractory lining replacement (costs of bricks for both “working” and “safety” linings plus labour).

The costs of gunning repairs to the lining (materials are reduced from 2 to 0.6 kg/tonne leading to a saving of $0.35/tonne).

The “outage” time decreased from 40 to 10 d/year or from 81 to 11 d/year and furnace availability increased from 78 to 97.5%.

Installations cost 0.1 to $1.0 million, and payback can be as high as $300 000 per month, leading to rapid payback.

Reduced CaO costs.

The downtime for a furnace reline is 3–24 days (depending on BOF size) and this must be offset against the time required for slag splashing (3–4 min per heat). The BOF utilization ratio has increased significantly with the introduction of slag splashing but the increase in production will depend upon the availability of hot metal and the logistics of each individual shop. In some shops severe build-up of slag in the bottom of the vessel has led to the abandonment of the bottom-stirring function resulting in a loss in yield which must also be taken into consideration.

Some shops have reported an increase in gunning costs in the later stages of a campaign. These result in increased costs and lead to the view that there is an “optimum lining life”.

Some shops have reported an increase in gunning costs in the later stages of a campaign. These result in increased costs and lead to the view that there is an “optimum lining life”.

Yan et al. reported that the overall cost index reached a minimum at 4 500 heats. In contrast, Lai et al. analysed plant data from these different plants (with BOF capacities of 90, 60 and 15 tonnes) and concluded there was no “optimum lining life” since savings were maintained with increasing lining life. The existence of an optimum lining life remains a contentious issue. On one hand, cost benefit analyses have been reported by Xiao et al. These focused on the economics of slag splashing for combined blowing. They tested these situations (i) where slag splashing resulted in blocking of the tuyeres (ii) where slag splashing did not block the tuyers and (iii) where slag splashing was not applied. The costs of individual items were detailed and the total cost is shown in Fig. 22(a).

They concluded that slag splashing with blocking of the tuyeres would only be cost efficient to 1 200 heats and would be more expensive for >1 200 heats. However, if no blocking of the tuyeres occurred (Fig. 22(b)), they found that slag splashing was economic up to 8 500 heats and suggested it could be used to 10 000 heats. Their analysis concluded that there was an “optimum lining life”. On the other hand, in some shops the amount of gunning cost remains constant. Thus providing the gunning costs do not exceed the costs of nitrogen and slag-containing materials, there should be no “optimum lining life” as witnessed by fact that ISPAT Inland’s No. 4 BOF shop reached 40 656 heats and another vessel has a lining life >62 000 heats.

9. Conclusions

(i) There are two different mechanisms involved in slag splashing, namely, slag washing and slag ejection.
(ii) The blowing characteristics (gas flow rate, lance
height and angle) are very important; there is a critical height giving maximum slag splashing for each specific gas flow, and the use of an angled jet also increases slag-planting.

(iii) The slag characteristics are also important and the slag should have the correct blend of high-melting and low-melting phases,

(iv) The low-melting phases provide good adhesion of slag with refractory since they are rich in FeO and react with carbon in the refractory to produce a foamy slag which infiltrates through the pores (created by the oxidation of the carbon) and subsequently reacts with the MgO from the refractories; this results in good adhesion of the slag with the lining.

(v) The high-melting phases provide protection of the refractory lining and a thermal barrier,

(vi) Ideally the thickness of the slag-splashed layer should match the overall erosion rate in the BOS process,

(vii) The optimum slag composition for slag splashing would appear to contain:

a. About 13% FeO,

b. Should give a slag supersaturated with MgO (>8%) to ensure that the slag becomes MgO-saturated rather than CaO-saturated to ensure that the high-melting phase MF is formed in preference to low-melting phases such as CF and C2F.

(viii) The slag viscosity may also be important; a fluid slag will run down the walls whereas a “dry” slag will not adhere well, but physical modelling trials have not taken into account the likelihood that the slag will be two-phase.

(ix) Knowledge of the effects of individual parameters (e.g. gas flow, lance height) can be used to produce more uniform slag layers.

Recommendations

Tsai et al. recommend that for good slag splashing:

(i) There is good control of the “end-point” FeO content and tapping temperature.

(ii) The Al2O3 content should be as low as possible.

(iii) If the SiO2 content of the slag is low e.g. ((CaO/SiO2)>5), SiO2 should be added.

(iv) Slag MgO contents should be >13% when FeO contents >20%.

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Nomenclature

\( A_n \): Nozzle area, (m²)

BOS: Basic Oxygen Steelmaking

\( C \): Concentration

\( D \): Diameter of vessel (m)

\( d \): Diameter of nozzle (m)

\( d_0 \): Diameter of droplet of slag (m)

\( F \): Force (N)

\( F_{Fe} \): Total Fe in end slag (%)

\( g \): Gravitational constant

\( H \): Height of vessel (m)

\( H_{slag} \): Depth of slag or bath (m)

\( h \): Height above slag line (m)

\( h_{cav} \): Depth of cavity created by jet penetration (m)

\( M_s \): Mass of slag (tonne or kg)

\( n \): Number of heats

\( Q \): Gas flow rate (m³ s⁻¹)

\( Q_{slag} \): Slag splashing rate (m³ s⁻¹)

\( T \): Temperature (°C)

\( T_{liq} \): Liquidus temperature (°C)

\( T_{tap} \): Tapping temperature (°C)

\( t \): Time (s)

\( u \): Gas velocity (m s⁻¹)

\( W \): Capacity of vessel (tonne)

\( \alpha \): Angle of inclination to the vertical

\( \gamma \): Surface tension of slag (N m⁻¹)

\( \eta \): Viscosity of slag (Pa s⁻¹, or dPa s⁻¹)

\( \nu \): Kinetic viscosity (m² s⁻¹)

\( \rho \): Density of slag (kg m⁻³)

Ceramic phase formulae e.g. \( MF = MgO \cdot FeO_3 \)

\( A: Al_2O_3 \)

\( C: CaO \)

\( F: Fe_2O_3 \)

\( M: MgO \)

\( S: SiO_2 \)

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