

A DYNAMIC SLAG-DROPLET MODEL FOR THE STEELMAKING PROCESS

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Synopsis: A dynamic slag-droplet model is developed on the basis of droplet formation behaviour in top-blown oxygen steelmaking converters and the multicomponent mixed transport control theory for slag-metal-gas reactions. The model is developed for the 315 t BOF's at Hoogovens IJmuiden. With the use of this model it is now possible to make quantitative predictions for the effect of changes in addition schemes as well as changes in hot metal composition. The characteristic evolution path for both slag and bath chemistry can be simulated by incorporating lance nozzle design characteristics and blowing regimes.

Key words : dynamic model, slag-metal reactions, droplet formation, BOF converter, Hoogovens IJmuiden, lance design

1. Introduction

Various experiments over the last years have given a reasonable insight in the evolution of the slag chemistry during the blow for the 315 t BOF's at Hoogovens IJmuiden [1]. The conclusions from these experiments regarding especially lime dissolution and lining wear are reflected in the present blowing and addition schemes, used in both Hoogovens' steelshops.

However, it has never been possible to make quantitative predictions of the changes in the slag evolution path for the situation that standard process conditions change (i.e. hot metal chemistry, addition practice). With the present version of the dynamic model it is possible to anticipate on new situations and to search for optimal conditions with a minimum of plant experiments.

The dynamic model is based upon the description of two important phenomena in basic oxygen steelmaking, i.e. the constant exchange between slag and metal phases and the continuous production of a large amount of metal droplets, covered with an oxidizing FeO-layer. For the first system the multicomponent mixed transport control theory is used. The adaption of this theory for a steelmaking converter by Deo et al. [2] is the original base of the present model. The second system, droplet generation, is based upon the interpretation of the work of Koria [3]. It is especially the combination of the oxidizing effect of droplet formation with the neutralizing effect of exchange reactions between slag and metal that will explain the characteristic reaction path of the steelmaking process.

The model also incorporates descriptions for scrap dissolution, lime dissolution and formation and melting of solid slag components.

2. Interfacial Reactions

For the calculation of the reactions at the various interfaces between slag, metal and gas a mixed transport model has been applied. Under the assumption that at the interfaces an instantaneous equilibrium exists the reactions are governed by the transport of elements in metal and oxides in slag towards or away from the interface [2,4].

By combination of the equilibrium and the mass balance equations (rate of transfer out of

metal = rate of transfer into the slag) a relation can be derived for the interfacial concentration of oxygen. After solving this equation by numerical methods the conservation equations for the various fluxes of elements and oxides can be calculated. Although the individual mass transfer constants have been estimated using published laboratory data, the actual rate of transfer is usually much faster than may be expected. This may be explained by the fact that the area, available for transfer is much larger than the nominal converter area due to the violent reactions in the BOF. The increase in the area is dependent on the phase of the process and may increase up to a factor 50 during the full decarburization. For all the above relations it is necessary to use the activities of the various components. For the metal phase this can be done using interaction coefficients. For the slag phase the IRSID version of the Kapoor/Frohberg model [5] has been extended with the oxides TiO_2 and P_2O_5 .

3. Oxygen Transfer

Before the reactions at the metal, slag and gas interfaces can take place a provision has to be made for the transfer of external gaseous oxygen to the system. Here a choice must be made out of two possibilities, i.e. direct decarburization (absorption of oxygen in the hot spot, followed by reaction of dissolved carbon with oxygen) or indirect decarburization (the reaction of oxygen to FeO, followed by a reduction of FeO with carbon to CO). Since direct decarburization can not explain the typical increase in FeO during the first period of the process the indirect decarburization is assumed to be dominant. Together with the proposed system for droplet formation behaviour this can very well be related to slag formation characteristics.

Once the oxygen has reacted to FeO the oxide layer will be swept away from the impact spot together with a large amount of metal droplets. During the lifetime of the droplet the enclosing oxide layer will react with the droplet contents. The overall reaction of FeO with carbon to CO should be regarded as the sum of the following reactions [6,7]



Initially the above reactions will be limited considerably when silicon is still present in the metal droplet. A layer of iron-silicate will form, which will slow down the reaction with carbon. Through diffusion of CO_2 across the silicate layer the decarburization will still proceed, but at a slower rate.

The extent of decarburization of the droplets depends on the residence time of the droplet in the slag. Taking into account that the rate constants of the gas-metal and gas-slag reactions are very high a residence time of only a few seconds is sufficient to obtain almost complete decarburization.

4. Droplet Formation Behaviour

A large amount of metal droplets, covered with an oxide layer is continuously ejected from the jet cavity. Recent studies at Hoogovens [8] using the work of Korja [3] and He [9] have been used to calculate the amount and the specific surface area of the droplets. The effect of lance design parameters, such as nozzle diameter, nozzle angle and also the blowing rate and the lance height schedule can be incorporated. The total amount of droplets (the iron conversion) can be calculated from the Weber number. The second important parameter, the size distribution, is determined by the Rosin-Rammler-Sperling distribution. The fraction RF of particles larger than a given diameter d is described by

$$RF = (0.001)^{(d/d\text{-limit})^{1.26}} \quad (3)$$

The diameter d-limit is given by :

$$d\text{-limit} = 5.513 \cdot 10^{-3} \cdot [10^6 \cdot d_t^2 / h^2 \cdot P_a \cdot (1.27 \cdot (P_o/P_a) - 1) \cos(\theta)]^{1.206} \quad (4)$$

where d_t = throat diameter of nozzle
 P_o = supply pressure
 P_a = ambient pressure
 θ = nozzle angle
 h = lance height

Integration of the formula for size distribution and combination with the total mass of droplets gives the available surface area. In Figure 1 the iron conversion and the droplet surface area are presented as a function of the lance to bath distance for a 5-hole oxygen lance, designed for an oxygen blowing rate of $915 \text{ m}^3(\text{stp})/\text{min}$.

In this example, the characteristic lance to bath distance would be 2050 mm. This will correspond to an iron conversion of 27.1 tons/minute. For an average bath weight of 315 tons and a blowing time of 16 minutes this means that the bath is refreshed 1.4 times during the process due to droplet formation. The specific droplet area is found to be 0.287 m^2 for every m^3 of oxygen blown. This value corresponds to the generation of an extra reaction surface of 4.4 m^2 per second. This has to be multiplied with the residence time of the droplets which is estimated to be about 5 seconds (depending on the slag foam height).

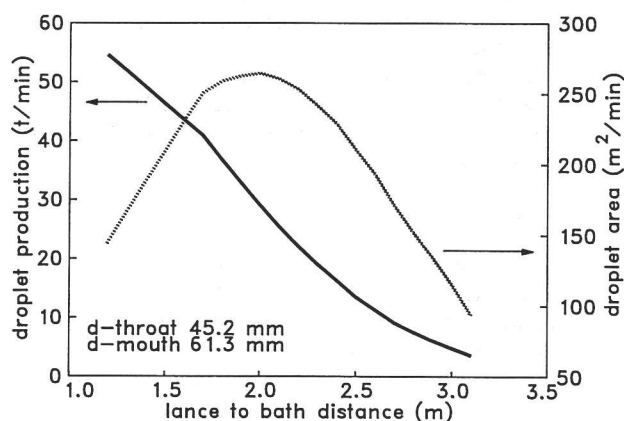


Fig. 1 Iron conversion and spec. area

5. Lime dissolution

For the dissolution of the lumpy lime, added during the process at various moments, a mechanism is chosen which takes into account the formation of a $2\text{CaO}\cdot\text{SiO}_2$ shell around lime particles. In the initial part of the blow a thin layer of $2\text{CaO}\cdot\text{SiO}_2$ will form around each lime particle thus limiting the direct dissolution of CaO in the slag phase. However, the dense layer of silicate will allow the diffusion of a solid solution of $\text{CaO}\cdot\text{FeO}$, which is constantly formed between the solid lime particle and the silicate layer. After a certain period, when the activity of $2\text{CaO}\cdot\text{SiO}_2$ in the slag drops, the silicate layer will also dissolve and a direct dissolution of CaO into the slag phase is possible.

In the model calculations the lime is assumed to be added in three batches, each with its own specific rate of addition. For all additions a distribution in 10 separate size fractions is made, each with its own initial characteristic diameter. In this way the total free surface of lime particles can be calculated.

For the first period, when a silicate layer is present, the dissolution of lime (in the form of $\text{CaO}\cdot\text{FeO}$) is considered to be represented by

$$J_{\text{CaO}} = k_1 \cdot A \cdot dt \cdot a_{\text{FeO}} \quad (5)$$

Here J_{CaO} is the flux of CaO into the slag in moles per second, k_1 is a mass transfer coefficient, A is the free surface area per fraction and a_{FeO} is the activity of FeO in the slag. The time step is denoted by dt .

In the second period, when the silicate layer has dissolved, the dissolution of CaO is relative to the surface and the activity of CaO in the slag.

$$J_{\text{CaO}} = k_2 \cdot A \cdot dt \cdot a_{\text{CaO}} \quad (6)$$

Another aspect of lime dissolution is the occurrence of "dry slags". This will take place when the activity of di- respectively tri-calciumsilicate is sufficiently high for the formation of a separate silicate phase in the slag. The remaining slag will become richer in FeO , MnO etcetera. A practical objection of the occurrence of these dry slags is the decrease of the liquid slag volume. A low slag volume causes a situation where metal droplets are not all caught up in the slag leading to skull formation on the lance or even in the boiler system if the droplets are blown out of the converter vessel. From a practical point of view it is therefore desirable to have a sufficiently large volume of liquid slag.

in the manganese content has been confirmed by sublance measurements in early stages of the blow. From the same experiments the strong dephosphorization in the initial part of the blow could also be observed. This is due to the fact that calcium phosphate is bound to the large amount of di-calciumsilicate that will form during the process. When the silicates will dissolve in the last part of the blow the phosphates are released quite rapidly, causing a phosphorus reversal to the metal. The final dephosphorization is taking place in the very last part of the process.

In Figure 3 the evolution of the slag composition is shown. An important aspect here is the sharp increase in (FeO). Although conditions are highly unfavourable for iron oxidation the effect of a small iron conversion during the initial period, when the lance to bath distance is still high, can be demonstrated. Compared to the main part of the blow the same amount of iron oxide, produced by the main oxygen lance, is compensated by a much smaller amount of iron droplets, thus offering only a small amount of carbon for the reduction of FeO. On top of this the presence of silicon in the droplets limits the decarburization reaction.

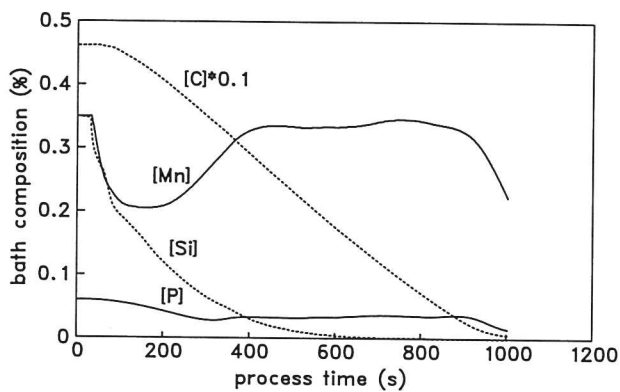


Fig. 2 Evolution of bath composition

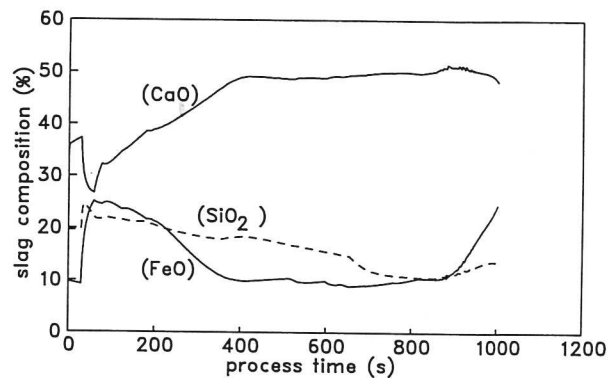


Fig. 3 Evolution of slag composition

In the next example the effect of the silicon level in hot metal is demonstrated through the evolution of the liquid slag volume. In Figure 4 the evolution of the liquid slag volume as a function of the [Si] level in hot metal (0.25 % and 0.35 % respectively). In the first situation the conventional steelmaking practice has been described, where in case of too low slag volumes a supplementary addition of lime will take place. In the second case a new experimental practice is described, where the deficiency in slag volume is supplied with cold slag. This cold slag is a mixture of converter steelmaking slag and slag from steel ladles. In the old situation only cold converter slag was used as a percentage of the lime addition. As can be seen from the curves the begin and end situations are comparable (this is also the case for bath and slag composition). However, during the main part of the blow the liquid slag volume using the new practice is considerably higher. As already has been explained the occurrence of a large liquid slag volume is beneficial in preventing the formation of metal skulls on lance, converter mouth and the boiler system. With the support of this information it has been

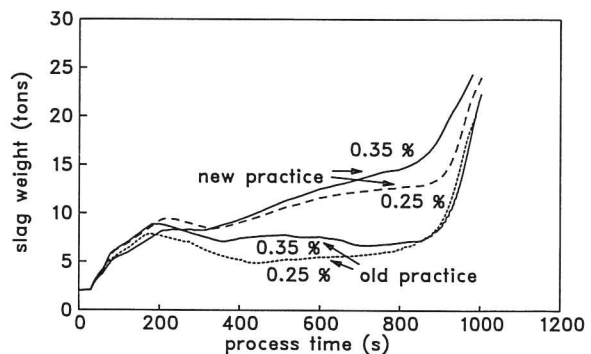


Fig. 4 Evolution of slag volume

6. Ore dissolution

In the dynamic model the dissolution of hematite ore pellets is considered. From recent studies at Hoogovens [10] it can be concluded, that the dissolution rate of pellets is proportional to the heating rate of the pellets. During the initial heating period a decomposition of Fe_2O_3 to FeO can be observed. A small amount of oxygen is released during that time. When the outer shell temperature of the pellet has increased enough a melting of FeO takes place. Complete dissolution follows in approximately 60 seconds.

7. Scrap dissolution

In the present version of the model the scrap dissolution is calculated based on a mathematical model by Asai and Muchi [11]. In this model it is possible to distinguish between initial freezing of scrap, dissolution of the frozen shell, direct dissolution of the scrap in the metal and finally melting of the remaining scrap. The unsteady state heat penetration in the scrap is calculated by numerical methods. The model can accept scrap of various sizes and analysis, each with a characteristic dissolution path.

A major problem, which has not yet sufficiently been solved, is the choice of the appropriate values for heat and mass transfer coefficients. Although a range of possible values has been reported none of the models allows for the fact that in the early part of the process the scrap is not present as individual pieces, but will be in the form of large irregular lumps of scrap and frozen metal. This leads to an uncertain combination of heat and mass transfer coefficients with the corresponding surface of exchange.

8. Slag foaming

The emulsification of the slag is calculated using the method proposed by Ito and Fruehan [12]. In this method the foam height is calculated from the gas residence time plus the viscosity, the surface tension and the specific weight of the slag. The foam height is adjusted for the amount of free particles present in the slag. These particles will increase the foam height through an increase in the apparent viscosity. In the dynamic model the foam height plays an important role since it controls the increase in surface area and the residence time of the metal droplets.

In principle this method can be used to predict the possible occurrence of too high foam levels. This may lead to overflow of the converter vessel (slopping).

9. Practical examples

In order to show some possibilities of the dynamic model a few situations have been worked out. Although the model has also successfully been tested on converters with a lower blowing rate and on the 100 ton converters of the Hoogovens BOS No. 1 the examples apply to the fast blowing converter (915 m(stp)/min) of BOS No. 2. Typical values for the examples are given in Table I.

Table I Typical production data for BOS No.2 , Hoogovens IJmuiden

hot metal charge	918	kg/ton	lime	33	kg/ton
			ore	16	kg/ton
hot metal	[Si]	0.350 %	cold slag	8	kg/ton
	[Mn]	0.410 %	spar	0	kg/ton
	[P]	0.065 %	soft burned dolomite	0	kg/ton
	[Ti]	0.060 %			
	temp	1375 °C	end point [C]	0.060 %	
			temp	1665 °C	
scrap charge	152	kg/ton			

The blowing conditions for this example have already been shown in section 4. In Figure 2 the evolution of the bath chemistry for the above situation is shown. The strong reduction

decided to lower the average silicon level to 0.35 % with a future plan for 0.30 %.

The increase of the amount of liquid slag is also possible through the addition of fluxing materials. Traditional fluxes are fluor spar, soft burned dolomite and manganese ore. One of the most effective methods of bringing more lime into solution is the formation of (MnO) through the oxidation of extra manganese out of hot metal. An advantage compared with the other fluxes mentioned above is the fact that no time is lost for heating up and dissolving the MnO. The effect of more [Mn] in hot metal is shown in Figure 5 via the ratio between solid slag (di- and tri-calciumsilicates) and the total amount of slag. Although it is clear that the amount of solid slag decreases considerably with the increase of manganese in hot metal it can also be observed that a certain amount of solid slag (and consequently an increased possibility of skull formation) will always exist. The use of very high values for manganese is prohibited because the final manganese at turndown would exceed the maximum levels given by quality requirements. As a compromise a working level of 0.41 % is now used for both steelplants, leaving a sufficient level of liquid slag during the process.

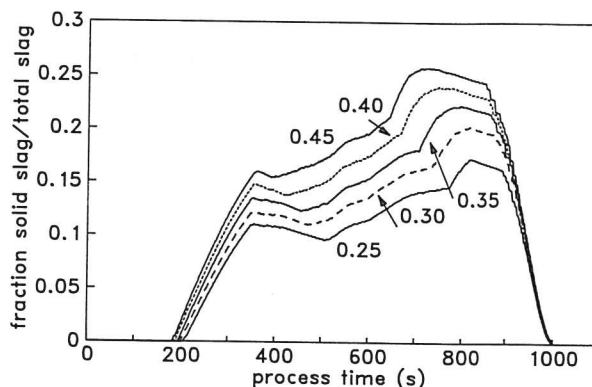


Fig. 5 Solid/liquid slag ratio

From a practical point of view the time required for calculation is an important factor for the applicability of the model. The examples shown above have been calculated using an IBM series 400 mainframe computer. For a time step of 1 second the computer time needed for one simulation is about 30 CPU. Of this computer time more than 90 % is used for calculation of slag activities.

10. Conclusions

1. The dynamic model can describe the typical evolution of both slag and bath chemistry using a combination of a mixed transport model and a droplet formation model.
2. With the introduction of the droplet formation theory the effect of blowing regimes and lance design parameters can be incorporated in the model.
3. The effect of process parameters on especially the physical slag condition can be simulated, thus providing a very useful practical application.

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