Analytical Evaluation of Heat Flow in Oxygen Steelmaking

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Dynamic models for a BOF (Basic oxygen furnace) process have been developed to quantitatively capture the variation in refining kinetics and heat flow during the blowing period. Previous studies have developed extensive models to understand the kinetics and reaction mechanisms for a BOF process. The understanding of heat flow during the refining period helps in optimizing the process terms of energy consumption and minimizing the overall excess heat (heat losses). The present work aims to develop an approach that will capture the heat flow during the blowing period once the refining profiles are known. In the present calculation the instantaneous heats were calculated based on the refining profiles from Cicutti et al.1) industrial trial and Implos pilot plant data.2) The developed model reveals different possibilities for process optimization by identifying the periods of overall excess energy formation. It was observed by compiling Cicutti’s data that an average of 7.5 MJ/min/t of hot metal excess heat is generated during the blowing period spanning from 6 to 14 minutes. Moreover, the present study demonstrates that the parameters such as scrap quantity, flux added, and oxygen flowrate can play a vital role in optimizing the process in terms of the utilization of the overall excess energy during the refining period.

KEY WORDS: heat flow; dynamic model; process control; optimization; basic oxygen steelmaking; overall excess heat; heat loss.

1. Introduction

In a top-blowing oxygen steelmaking process, a large amount of heat is generated due to the impinging action of oxygen jet with carbon saturated liquid bath resulting in exothermic reactions. The kinetic mechanism of oxygen reacting with impurities in the liquid bath has been extensively studied by several researchers and now exist several models capable of predicting the kinetics of oxygen steelmaking, as a function of different blowing parameters.3–11) In most cases, these models rely on particular assumptions on how temperature gradients in the furnace vary with time and without considering the overall excess heat or heat loss percentages. However, as oxygen steelmaking is an energy-intensive process, it is required to analyze the heat flow during the blowing period that provides an insight into the potential energy optimizing opportunities. To control and optimize the process, a heat flow model that captures instantaneous energy content during the process is required.

The heat aspects of the BOF process can be expressed as a function of the oxidation reactions and temperature of the bath. Previous researchers13,12–16) have estimated the temperature profile of the hot metal bath and found that bath temperature exhibit a linear relationship with the blowing time and quantity of oxygen blown. A comprehensive dynamic model and thermal characterization, proposed by Huber et al.17,18) for understanding the thermal behavior of the process was validated with industrial trials at Arcelor Mittal Dunkerque. The objective of the model was focused on calculating the evolution of slag, steel, and post-combustion temperature and predicts the heat transfer efficiency during the blowing period. The temperature profiles predicted by the model considers the possibility of post-combustion reaction heating the slag. It was also inferred that after reaching around 7 to 8 min, the slag temperature was found to be greater than steel temperature. However, the details pertaining to the formulation and calculation of the models are not available in the literature.

A recent paper by Biswas et al.19) predicts a non linear variation in temperature profile considering BOF as a 3 constantly stirred zones (Slag–metal–gas emulsion zone, lower part and upper part of the metal bath) with continuous heat and mass transfer. However, quantification of heats specially overall excess heat were not mentioned in the discussion. Several researchers have analyzed heat transfer aspects of the steelmaking process in terms of (a)
quantifying the temperature of the metal droplets;\textsuperscript{20–22} (b) calculating the heat released and transferred from the post-combustion reaction in a foaming slag;\textsuperscript{23–26} (c) improving the energy efficiency of the process by increasing the scrap melting (by 3 to 6\%) using the heat of post-combustion;\textsuperscript{27–29} and (d) investigating the heat transfer mechanism of scrap melting and dissolution.\textsuperscript{30–37}

The industrial, experimental, and model studies show that the BOF process has been reasonably understood through dynamic kinetic models in terms of predicting refining profiles, achieving various end composition, and tap temperature. To the best of the authors' knowledge, there are no details available in the open literature discussing the evolution and quantification of heat in different zones (hot metal, slag, flue gas, scrap melting, overall excess heat) at each instant of time during the refining period for a BOF process. Therefore, the present work focuses to develop an approach that will provide an insight to capture the heat flow during the blowing period when the refining profiles are known. For the present study the refining profiles from the industrial study conducted by Cicutti \textit{et al.}\textsuperscript{1} and are considered. The implication of this research provides opportunities to optimize the overall excess heat generated during the process.

2. Methodology

To determine the heat flow during the refining process, the energy content of the melt was calculated by applying an instantaneous heat balance. The heat generation is mainly contributed from different exothermic reactions such as decarburisation and desiliconisation, and oxidation of other metallic elements (phosphorus, manganese, iron) as well as the CO to CO\textsubscript{2} post-combustion in the converter. The generated heat is mainly utilized for scrap melting, flux dissolution, and increasing temperature of the hot metal bath and slag. These components of heat are therefore retained within the converter. Heat does escapes from the BOF in the form of heat lost through converter walls and neglected components such as heat of dust (iron fumes), bottom blowing gas, heat taken up by lance cooling water, heat of formation of solid slag precipitates such as C\textsubscript{2}S (2CaO.SiO\textsubscript{2}), C\textsubscript{3}P (3CaO.P\textsubscript{2}O\textsubscript{5}) or undissolved fluxes and loss on ignition. The closing of the dynamic heat balance quantifies the instantaneous overall excess heat that goes in form as heat loss during the blowing period.

The calculations of the heat flow model were carried out using a pseudo-transient heat balance approach. At every instance, the heat of steel, slag, flue gas, scrap melting,

![Fig. 1. Schematic representation of heat flow calculation. The numbers in the bracket represent the operation/blowing time in minutes.](image-url)
and overall excess heat was computed considering the heat of hot metal and heat of reaction as input. The schematic representation of the dynamic heat balance model is shown in Fig. 1. The results from the dynamic heat balance calculations were plotted with heat content expressed in GJ/min along the y-axis and blowing time expressed in minutes along the x-axis. As there exist no previous heat flow models or experimental data to compare, the area under the heat flow curve is calculated to validate the results against the overall static heat balance model.

The current study calculated the instantaneous components of heat based on Cicuttì’s measured refining profiles and scrap melting profile calculated Dogan et al. as shown in Fig. 2. The industrial trials of Cicuttì’s were conducted in a 200-ton converter and inert gas was blown through the bottom. The lance height was maintained at 2.5 m up to 4

![Fig. 2.](image-url)

(a) Mass of Slag and Scrap; (b) concentrations of Si, Mn, P in the melt; (c) slag composition; (d) decarburization profile; and (e) lance height variation as a function of evolution of blow from Cicuttì et al.1,3,4)
minutes of the blow and then reduced to 2.2 m and the blowing rate of oxygen was 620 Nm³/min. Samples were collected at different intervals during the blowing period. The initial samples were collected at 2.2 min and were used as the starting point of profiles as shown in Fig. 2. The results from industrial trials captured the evolution profiles of the bath, slag and emulsion chemistry for a top blown oxygen steelmaking process. It needs to be acknowledged that Cicuttis’s plant study has not recorded the profile of P2O5 composition in the slag. Therefore, the present study considers the P2O5 composition prediction from the numerical study of Bapin et al.39) that was carried out with Cicuttis’s3) input data. To incorporate the refining profiles into the heat flow model, empirical relations expressing refining rates as a function of blowing time were derived from the Cicuttis’s refining graphs (given in Appendix 1). Likewise, empirical relations of refining profiles were derived for Imphos plant data. The Imphos experiments were conducted for 23 heats in a 6-ton pilot plant and samples of slag-metal emulsion at different heights were monitored in every 2-minute time interval. Out of 23 heats, a sample heat set “S1828” is selected as it has a simple near-constant P removal rate of 0.004%/minute throughout the blow. Therefore, the current study, data at the start of the blow are not available as the initial sampling is collected at 2.2 min after the start of the blow. Therefore, the current model uses values and data from 2.2 min of the blow onwards.

2.1. Formulation and Assumptions

With the derived empirical relations, the mass of oxides formed, scrap melted and gases formed were captured and the equivalent heats of respective components were calculated at different intervals of blowing period. As depicted in Fig. 3, the exothermic heat from the oxidation is mainly used for scrap melting, heating the steel bath, slag, sensible heating of flue gas and some negligible amount of heat may consume to heat the injected gas from the bottom. The overall excess heat represented in Fig. 3 expresses the sum of heat lost through converter walls, heat loss through the converter mouth and neglected components such as heat of dust (iron fumes), bottom blowing gas, heat taken up by lance cooling water, heat of formation of solid slag precipitates such as C₆S (2CaO·SiO₂), C₃P (3CaO·P₂O₅) or undisolved fluxes and loss on ignition. The reactions considered and their respective enthalpies and heat of dissolutions are given in Tables A-1 and A-2 (Appendix 3). The equations used for calculating the heat of dissolutions were taken from Healy et al. 39) study on a static heat balance. Therefore, at any instantaneous ∆t, the following equations can be developed,

\[ \Delta Q_{\text{Reaction}} = \Delta Q_{\text{Hot Metal to Steel}} + \Delta Q_{\text{Slag}} + \Delta Q_{\text{Flue gas}} + \Delta Q_{\text{Scrap Melting}} + \Delta Q_{\text{Excess Heat}} \quad \ldots (1) \]

This can be done.3–9,19) The approach outlined in the current study could be improved by incorporating dynamic chemical models in future work.

In the calculations, a number of assumptions were taken and explained in more detail below:

• In Cicuttis’s study, data at the start of the blow are not available as the initial sampling is collected at 2.2 min after the start of the blow. Therefore, the current model uses values and data from 2.2 min of the blow onwards.

• Previous studies have predicted temperature profiles of the melt and slag in a BOF process through

![Fig. 3. Schematic representation of heat of reaction utilized by various output heat components.](image-url)

![Fig. 4. Post-combustion profile used for heat flow calculation. (Online version in color.)](image-url)
balancing the heat input and heat output without considering the overall excess heat percentage (i.e., overall excess heat% or overall heat loss% = 0) during the blowing period. However, as the present study intends to quantify the overall excess heat generated during the process, a linear temperature profile (which was used to calculate the refining profiles) from Cicutti’s plant data is considered. In Cicutti’s heat data,1) the hot metal temperature profile is assumed to vary linearly from 1350°C to 1650°C.38) Similarly, the slag temperature was assumed to be 100°C greater than the hot metal temperature. Therefore, the following equations38) were used in the calculations.

\[ T_{h}(t) = T_{s}(t) + 18.75 \times t \]
\[ T_{s}(t) = T_{sb}(t) + 100 \]

- In addition to evolution profiles of the bath, slag, emulsion chemistry, and temperature, the rate of scrap melting is required as input for the model to calculate the overall excess heat during the blowing period. According to the model developed by Dogan et al.4) (developed based on Cicutti’s heat data input1), the scrap quantity weighing 30 tons, melts and dissolves linearly before 7 minutes of oxygen blow. Therefore, a linear scrap melting profile proposed by Dogan et al.4) was assumed for the present calculation. Once again, more sophisticated models could be used but this simple model was used merely to demonstrate the general principle.

- To compute the heat of post-combustion, the PCR profile (post-combustion ratio, defined as the ratio of CO₂/(CO + CO₂) from plant observation was considered as shown in Fig. 4.) The profile shows that post-combustion declines linearly from 0.2 to 0.08 by 3 minutes and maintains a value of 0.08 until 14 minutes and increases linearly to 1 by the end of the blow. In addition, the temperature of off-gas was assumed to be the average temperature of hot metal and slag.39)

3. Results and Discussion

The results from the heat flow model provide an understanding of the evolution of heat during the refining period. As no previous studies/datas are available to validate the instantaneous heat during the blowing period, the integrated results obtained from heat flow model were compared against the results from the static heat balance model40) executed with Cicutti’s and Imphos industrial study heat data1) as input. The individual heat components (heat of reaction, slag, flue gas, hot metal to steel, scrap melting, and overall excess heat) of the model were obtained by integrating the curve over the entire blow period and the results were compared with the overall static heat balance model as shown in Figs. 5 and 6. The heat of hot metal to steel represents the sensible heat required for raising

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**Fig. 5.** Comparison of predicted dynamic heat balance values with static heat based on the data from Cicutti et al.¹ industrial trial. (Online version in color.)

**Fig. 6.** Comparison of predicted dynamic heat balance values with static heat based on the data from Imphos heat set S1828.² (Online version in color.)
**Table 1.** Some input of the model taken from Cicutti et al.\textsuperscript{1)} and Imphos\textsuperscript{2)} with a starting point of 2.2 minutes.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cicutti et al.\textsuperscript{1)}</th>
<th>Imphos (S1828)\textsuperscript{2)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot metal</td>
<td>170 t</td>
<td>5.060 t</td>
</tr>
<tr>
<td>Composition</td>
<td>C-4.0%, Si-0.35%, Mn-0.4%, P-0.08%</td>
<td>C-4.1%, Si-0.54%, Mn-0.45%, P-0.08%</td>
</tr>
<tr>
<td>Scrap</td>
<td>30 t</td>
<td>0.5 t</td>
</tr>
<tr>
<td>Flux</td>
<td>Lime-7.6 t, Dolomite-2.8 t, Cuarcite-0.8 t</td>
<td>Lime-0.3 t</td>
</tr>
<tr>
<td>Oxygen Blown</td>
<td>620 m\textsuperscript{3}/min. Six-hole lance.</td>
<td>17 Nm\textsuperscript{3}/min, single hole lance</td>
</tr>
<tr>
<td>Initial hot metal temperature</td>
<td>1350°C</td>
<td>1350°C</td>
</tr>
<tr>
<td>Tapping Temperature</td>
<td>1650°C</td>
<td>1723°C</td>
</tr>
<tr>
<td>Mass of Slag</td>
<td>15 t</td>
<td>0.404 t</td>
</tr>
<tr>
<td>PCR</td>
<td>0.08</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Fig. 7. Variation in heat of reaction during the blowing period based on Cicutti et al.\textsuperscript{1)} refining profile. (Online version in color.)

Fig. 8. Variation in heat of reaction during the blowing period based on Imphos S1828\textsuperscript{2)} refining profile. (Online version in color.)

Fig. 9. Heat of reaction contributed by individual oxidation reactions (a) Si, Mn, Fe, and P (b) C during the blowing period based on Cicutti et al.\textsuperscript{1)} refining profile. (Online version in color.)

Fig. 10. Heat of reaction contributed by individual oxidation reactions (a) Si, Mn, Fe, and P (b) C during the blowing period based on Imphos S1828\textsuperscript{2)} refining profile. (Online version in color.)
the temperature of hot metal (to steel) during the blowing period. The calculations were carried out with the inputs given in Table 1 from Cicutti’s1) and Imphos industrial study.2) Figures 5 and 6 infer that the approach used for the heat flow calculation agrees well with the trend of overall static heat balance and provides some confidence in the approach taken in this study. The static heat balance model formulated by Madhavan et al.40) considers the input masses from static mass balance and calculates the heat input, heat of reaction, heat output, and overall excess heat based on the initial and final thermal data. The possible reasons for the variation in the values of the heat flow model compared to the static model can be due to: (a) R² errors associated with the empirical relations (given in Appendix 1) expressing the refining profiles (b) the integrated heat values from the model is dependent on the refining path.

The heat of reaction profile during the blowing period is shown in Figs. 7 and 8. The results shown in Fig. 7 were calculated by considering the Cicutti’s profiles of oxide formation shown in Fig. 2(c) and the decarburization profile shown in Fig. 2(d). Similarly, Fig. 8 depicts the heat of reaction profile predicted based on Imphos S18282) refining profiles given in Fig. A-1 in Appendix 2. The total heat liberated during oxidation is shown in Figs. 7 and 8 accounts to around –900 MJ/t of hot metal and –852 MJ/t of hot metal respectively. The heat of reaction during the blowing period depends on a number of parameters such as the amount of impurities present in the hot metal (i.e. composition of hot metal), final composition of steel, the quantity of oxygen blown, and the lance height. However, the trend of heat of reaction profile can be explained by analyzing the individual heat of reaction shown by Figs. 9 and 10.

As higher percentage of impurities were present during the initial phase of the blow, higher amount of heat was generated by the oxidations of Si, Mn, Fe, and P during 2 to 5 minutes (Figs. 9 and 10). Based on Cicutti’s refining data, after 5 minutes of the blow, the predicted heat contributed via oxidation of carbon was more dominant compared to other oxidation reactions as shown in Fig. 9(b). Therefore, a constant heat of reaction of −10 GJ/min was maintained within the converter between 5 to 14 minutes of the blow as shown in Fig. 7. Whereas, towards the end of the blow 14–16 minutes then heat of −10 GJ/min (Fig. 7) is maintained due to the heat generated from Iron oxidation as represented by Fig. 9(a). It should be noted that till the first half of the blow the trend of heat of reaction profile predicted for Imphos data is similar to Cicutti’s data. However, for the Imphos heat set S1828, the FeO formation sharply increased from the 12th minute till the 16th minute of the blow as shown in Fig. 10(a). Therefore the heat contributed by Fe to FeO reaction from 12 min to 16 min is −39.76 MJ/t of steel for Cicutti and −75.88 MJ/t of steel for Imphos. It should be mentioned that during the middle of the blow, the formation of FeO is decreasing as shown in Figs. 2(c) and 13(c). Therefore, Figs. 9(a) and 10(a) shows that the reduction in the formation of FeO absorbs some amount of energy resulting in the curves represented by the blue line (Figs. 9(a) and 10(a)) to proceed in the positive value during the middle stage of the blow.

The heat outputs shown in Fig. 11 are expressed in GJ/min to signify the instantaneous heat utilization by different heat components. During the initial phase of the blow, the heat from the exothermic reactions were mainly consumed for heating the hot metal to steel, heating of slag, scrap melting and dissolution, and flue gas as shown in Figs. 11(a), 11(b), 11(c), 11(d). According to the scrap melting profile predicted by Dogan et al.,4) before 7 minutes the entire amount of scrap gets dissolved and the present calculation quantifies the scrap melting and dissolution heat to be around 1.25 GJ/t of scrap or 312 MJ/min/t of scrap. The other component of heat output shown in Fig. 11(d) denotes the sensible heat of flue gas composed of CO and CO₂ that
consumes around 170 MJ/t of hot metal by the end of the blowing period. Predictions carried out with Imphos data also shows a similar trend for heat output components (hot metal to steel, slag, scrap melting, flue gas) as shown in Fig. A-2 (Appendix 2).

The significant implication from the heat flow model lies in quantifying the overall excess heat (defined as the difference between heat input and heat output) with respect to the blowing period. The results from Figs. 12(a), 12(b) highlights the deficiency of heat inside the converter during the initial phase of blow resulting in the overall excess heat to be negative (-ve excess heat implies that the current heat content is lower than the previous heat content.). This implies that if scrap melting and dissolution take place via heat transfer an additional amount of heat is required till 6 minutes of the blow. However, in the initial stage when the temperature of the hot metal is less than the melting point of the scrap, the diffusive scrap melting occurs which means that the difference between the carbon concentration plays a major role than temperature. Previous studies from Shukla et al.34) also highlights that in the early part of the process, scrap dissolution progresses due to mass transfer (heat availability may not be a limiting factor). Therefore, the present study reassures the possibility that scrap melting and dissolution is dependent on (a) mass transfer due to carbon concentration gradient (b) temperature profiles of hot metal and slag and (c) combined effect of both.

The instantaneous overall excess heat calculated from the heat flow model highlights the possibility of optimizing the process. Figure 12(a) predicted from Cicutti’s data shows that from 6 to 14 minutes the excess amount of heat generated. However, the overall excess heat is not utilized and goes in from as heat loss. This accounts for an average excess heat of 1.5 GJ/minute or 7.5 MJ/min/t of hot metal. On the other hand, overall excess heat predicted from the Imphos heat set as shown in Fig. 12(b) suggests that there is an increasing trend of excess heat (from 0 to 0.15 GJ/min or 0 to 30 MJ/min/t of hot metal) in the second half of the blow. This is attributed due to increased Fe oxidation after 10 minutes of the blow. The calculated overall excess heat expresses the sum of heat lost through converter walls, heat loss through the mouth, and neglected components (heat of dust, bottom blowing gas, heat taken up by lance cooling water, lance scull, mouth scull, ejections from vessel, heat of formation of solid slag precipitates such as C2S, C3P or undissolved fluxes and loss on ignition). From the perspective of heat optimization, repercussion from this study suggests that overall excess heat during this period can be minimized by

3.1. Controlling the Oxygen Flow Rate

The oxygen flow rate determines the heat generated via the exothermic reactions. Based on the analysis of Cicutti’s profile, the present study qualitatively anticipates that if the oxygen flow rate is decreased at the middle of the blow then the corresponding overall excess heat generation can be minimized.

3.2. Lance Position

In addition to the oxygen flow rate, lance height plays a vital role in refining kinetics, and thus it can affect heat generation rate. Previous studies41–43) have pointed out that lance height influences the rate of decarburization, impact area of the hot spot, FeO formation, and droplet generation (decreases in lance height increases the droplet generation). This can indirectly influence the excess heat flow. Therefore, the present study suggests the effect of lance height on excess heat as a case for future study to understand the ways to minimize overall excess heat.

3.3. Intermittent Feeding of Scrap during the Blow

The present study suggests intermittent feeding of scrap as one of the ways to effectively utilize the overall excess heat. In the recent research on “Use of Metallized Raw Materials in Electric Furnace Steelmaking”44) the possibility of using a bunker feeding system was discussed as one of the ways for continuous feeding of scrap into the converter. Since overall excess heat is available during the middle of the blow, the authors would like to suggest the intermittent feeding of scrap through a bunker feeding system as an idea to effectively utilize the overall excess heat in the BOF converter.

![Fig. 12. Overall Excess heat during the blowing period based on profiles of a) Cicutti et al.]() and b) Imphos plant data.]() (Online version in color.)
3.4. Optimizing the Scrap Mix (Heavy and Light Scrap)

The best way to minimize overall excess heat in the system is through melting scrap. However, the ratio of heavy to light scrap matters because heavier scrap is more difficult to melt compared to light scrap. In the present study, the effect of scrap type is not considered and scrap is assumed as bulk and the heat of scrap melting is considered based on the linear scrap melting profile of Dogan et al. However, it is anticipated that considering the scrap based on light and heavy type will alter the linear scrap melting profile and thus the overall excess heat generation. Since this case is beyond the scope of the present work, it can be considered for future studies.

3.5. Calculated Addition of Flux

The recent mass balance developed by Madhavan et al. quantifies the mass of slag (that can be expressed as flux required) based on the desired levels of P, C in steel and tapping temperature. If an additional amount of flux is added then the overall excess heat will be minimized due to an increase in the heat of slag (this heat can be retained within the converter).

In general, the present study intends to understand how heat flow varies during a BOF process if the refining profiles are known. On the other hand, the authors would like to address the limitations of the present model that can be considered for future studies. The weakness of the model can be attributed due to factors such as:

a) The assumption of a linear temperature profile for hot metal and slag. However, this needs to be justified that to balance the heat at any instant of time the mass of the components, corresponding temperatures, and heat loss/excess heat percentage are required. As the present study intends to provide an idea of overall heat flow and thereby understanding the overall excess heat at any instant of time, an assumption of the temperature profile is required. The future studies are focused to formulate a mathematical model that expresses overall heat as a function of temperature. This will help to simultaneously predict the instantaneous temperature profile and overall excess heat during the blowing period.

b) The present model assumes a linear scrap melting profile concluded from the study of Dogan et al. which conveys that by 40% of the blow scrap dissolution is completed. It needs to be emphasized that the effect of scrap mix also matters on the heat of scrap melting profile and thus the overall heat flow which is not considered in the present study.

c) Neglected parameters such as retained slag in the vessel, turnaround period, and lining wear can result in the deviation of heat flow values.

It should be acknowledged that the heat flow model is developed based on the previous industrial study of Ciccuti et al. and from kinetic models of Dogan et al. and Bapin et al. that uses Ciccuti’s heat data for predicting refining profiles. Similarly, the heat flow model is compiled with the Imphos plant data and profiles of heat evolution were predicted based on the refining profiles given in Fig. A-1 (Appendix 2). The strength of the present work lies in the development of a simple approach that can be used to understand the energy flow during the process. In addition to that, the possibility to optimize the process was suggested by considering the overall excess heat variation during the refining period. However, to successfully execute the heat flow model, the predicted results of refining profiles from the kinetic models are required. Therefore, the present approach can be integrated as a sub-module with the kinetic model for evaluating the overall heat flow.

4. Conclusions

An approach for calculating heat flow for a BOF process has been proposed which can be integrated with any kinetic models that predict refining profiles, the evolution of slag and steel to calculate the heat flow contributed by various heat components during the blowing period. Using Ciccuti’s and Imphos data, the following conclusions are inferred from the present study:

- Based on Ciccuti’s data, the heat liberated from the exothermic reaction accounts to around −900 MJ/t of hot metal. The heat generated at the initial phase of the blow was contributed by the oxidation of Si, Mn, Fe, and P. Afterwards from 5 to 14 minutes of the blow, the heat of C oxidation dominates compared to other exothermic reactions. However, the heat of reaction predicted from the Imphos data shows that in the second half of the blow the combined effect of C and Fe oxidation results in the heat of reaction to increase from −0.2 GJ/min to −0.4 GJ/min.
- The model predicts the instantaneous heat required by various components of the system, such as the hot metal, slag, scrap, and flue gases. Considering the linear scrap melting profile for Ciccuti’s and Imphos data, the model predicts that around 312–350 MJ/min/t of scrap heat is required in the first 6 minutes of the blow for the complete dissolution of scrap.
- The excess heat profile predicted from Ciccuti’s data shows that an average of 7.5 MJ/min/t of hot metal excess heat is available during the middle of the blow. On the other hand, the prediction from Imphos data shows that due to the combined effect of C and Fe oxidation, around 0 to 30 MJ/min/t of hot metal excess heat is available in the second half of the blow.

Acknowledgment

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Nomenclature

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<tr>
<th>Symbol</th>
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<tr>
<td>W_{HM}</td>
<td>Weight of Hot Metal (t)</td>
</tr>
<tr>
<td>W_{Scrap}</td>
<td>Weight of Scrap (t)</td>
</tr>
<tr>
<td>W_{Steel}</td>
<td>Weight of Steel (t)</td>
</tr>
<tr>
<td>W_{Slag}</td>
<td>Weight of Slag (t)</td>
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<td>W_{Flue}</td>
<td>Weight of Flue gas (t)</td>
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<td>Heat of slag</td>
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<tr>
<td>Q_{Flue}</td>
<td>Heat of flue gas</td>
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<tr>
<td>X</td>
<td>% of impurity in hot metal/slag/flue gas</td>
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\[
\text{Fe}_{\text{Scrap, steel}}: \text{Fe\% in Scrap, steel} \\
T_{\text{steel}}: \text{Steel Temperature (K)} \\
T_{\text{H}}: \text{Hot Metal Temperature (K)} \\
T_{\text{flue}}: \text{Flue Gas Temperature (K)} \\
T_{\text{melt}}: \text{Melting point of steel (K)} \\
L: \text{Latent Heat (kJ/kg)} \\
PCR: \text{Post Combustion Ratio} \\
HDiss\_x: \text{Heat of dissolution kJ/kg of X} \\
C_{\text{X}}: \text{Specific Heat kJ/kg K of X} \\
H_{\text{Ren}}\_x: \text{Heat of Reaction kJ/kg of X.}
\]

REFERENCES


Appendix 1:

To proceed with the calculations for dynamic heat balance, the refining profiles of the impurities, evolution profiles of slag and hot metal and dissolution profiles of scrap with respect to blowing period is required. The present model captures the profiles from Ciciutti et al. and Dogan et al. study as depicted in Fig. 2. The profiles were expressed via empirical relations as given by Eqs. (8) to (20) with an average R² of 0.95 and were incorporated into the dynamic heat flow model.

\[
W_{\text{Slag}}(\text{tonne}) = W_{\text{HMM}}(\text{tonne}) + W_{\text{Scrap}}(\text{tonne}) - m_{\text{impurity}} \cdot t \\
W_{\text{Scrap}}(\text{tonne}) = 0.0116833 \cdot t^3 - 0.318563 \cdot t^2 + 3.08027 \cdot t - 1.75572 \quad (2.2 \leq t \leq 16) \\
W_{\text{Slag}}(\text{tonne}) = 0.861254 \cdot t^2 - 14.823 \cdot t + 57.40 \quad (2.2 \leq t \leq 16)
\]

Variation in Hot Metal Composition

\[
% C = 0.0015 \cdot t^3 - 0.03534 \cdot t^2 - 0.0801045 \cdot t - 4.6 \quad (11) \\
% Mn = \\
\begin{cases} 
0.0006041 \cdot t^3 - 0.0033 \cdot t^2 - 0.05741 \cdot t + 0.431; & (2.2 < t < 11) \\
-0.0001225 \cdot t^3 + 0.008217 \cdot t^2 - 0.175101 \cdot t + 1.23; & (11 \leq t \leq 16)
\end{cases}
\]

(12)

\[
% P = \\
\begin{cases} 
0.0001316 \cdot t^3 - 0.00194 \cdot t^2 - 0.00237 \cdot t + 0.08; & (2.2 < t < 11) \\
0.0006371 \cdot t^2 - 0.0223425 \cdot t + 0.205; & (11 \leq t \leq 16)
\end{cases}
\]

(13)
Variation in Slag Composition

\[
\begin{align*}
\% \text{Si} &= -0.001609t^3 + 0.036t^2 - 0.257t + 0.614; \quad (2.2 < t < 9) \\
0.0003t^2 - 0.0096t + 0.098311; \quad (9 \leq t \leq 16) \\
\end{align*}
\] ........................................ (14)

\[
\begin{align*}
\% \text{FeO} &= 0.008t^4 - 0.198t^3 + 1.515t^2 - 5.96t + 40.63; \quad (2.2 < t < 13) \\
&= -0.1507t^2 + 6.56225t - 46.3; \quad (13 \leq t \leq 16) \\
\end{align*}
\] ........................................ (15)

Fig. A-1. (a) Mass of Slag and Scrap; (b) concentrations of Si, Mn, P in the melt; (c) slag composition; (d) decarburization profile; (e) bath temperature as a function of evolution of blow from Imphos pilot plant data.
Appendix 2: Implementing Dynamic Heat Flow Model with Imphos Plant Data

A2.1. Refining Profiles

A2.2. Imphos Heat Flow Results from Dynamic Model

Appendix 3:

Table A-1. Heat of Reactions at 298 K \(^{39,40,46,47}\)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Heat of Reaction (kJ)</th>
<th>Per Kg of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>[C] + 1/2O(_2) → CO</td>
<td>-9 191.82</td>
<td>C</td>
</tr>
<tr>
<td>[C] + O(_2) → CO(_2)</td>
<td>-32 729.4</td>
<td>C</td>
</tr>
<tr>
<td>[Si] + O(_2) → (SiO(_2))</td>
<td>-32 157.1</td>
<td>Si</td>
</tr>
<tr>
<td>[Fe] + 1/2 O(_2) → (FeO)</td>
<td>-4 775.023</td>
<td>Fe</td>
</tr>
<tr>
<td>[Mn] + 1/2 O(_2) → (MnO)</td>
<td>-6 999.61</td>
<td>Mn</td>
</tr>
<tr>
<td>2[P] + 5/2 O(_2) → (P(_2)O(_5))</td>
<td>-26 332.5</td>
<td>P</td>
</tr>
</tbody>
</table>

Table A-2. Heat of dissolution of impurities in liquid Fe and oxides in slag \(^{39,40,46,47}\)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Heat of dissolution (kJ)</th>
<th>kg/kg of:</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(graphite) = C(dissolved)</td>
<td>1 886.56 + 129.6 x % C</td>
<td>C</td>
</tr>
<tr>
<td>Si(liquid) = Si(dissolved)</td>
<td>-5 269 + 334.4% C + 142.12% Si</td>
<td>Si</td>
</tr>
<tr>
<td>Mn(liquid) = Mn(dissolved)</td>
<td>0</td>
<td>Mn</td>
</tr>
<tr>
<td>1/2 O(_2)(gas) = O(dissolved)</td>
<td>-7 315</td>
<td>O</td>
</tr>
<tr>
<td>1/2 P(_2)(gas) = P(dissolved)</td>
<td>-3 940.6</td>
<td>P</td>
</tr>
<tr>
<td>SiO(_2) dissolved</td>
<td>-413.33</td>
<td>SiO(_2)</td>
</tr>
<tr>
<td>FeO(_2) dissolved</td>
<td>1 873.7</td>
<td>FeO(_2)</td>
</tr>
<tr>
<td>FeO dissolved</td>
<td>1 083.3</td>
<td>FeO</td>
</tr>
<tr>
<td>MgO dissolved</td>
<td>1 645</td>
<td>MgO</td>
</tr>
<tr>
<td>CaO dissolved</td>
<td>-112.5</td>
<td>CaO</td>
</tr>
<tr>
<td>MnO dissolved</td>
<td>638</td>
<td>MnO</td>
</tr>
</tbody>
</table>