Heat Transfer in a BOF Converter

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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 BOF process is successful in terms of the high production rate (>200 t/h) and the high quality of steel produced. However, the process needs to be optimized in terms of energy requirement and utilization. For example, a proper understanding of the heat evolution and heat losses during the blowing period would allow the operator to fix the amount of scrap added. This will aid in the efficient transformation of raw material to steel in a sustainable manner.

The understanding of heat flow during the refining period helps in optimizing the process in terms of energy consumption, minimizing heat loss, and reducing CO2 emissions. In the context of heat transfer, the studies conducted have been mainly focused on the overall energy flow analysis (that includes the energy needed for combined Iron and Steelmaking via different process routes) or exergy analysis using the concepts of thermodynamics. To the best of the author's knowledge, no general heat transfer model for BOF technology is available in the open literature that describes the evolution of heat and heat transfer rate during the blowing period. Therefore, the present research highlights the importance of heat transfer in the oxygen steelmaking process and addresses research questions such as:

1. How does the temperature during the blowing period vary at different locations inside the steelmaking converter?
2. How efficient is the steelmaking process in terms of environmental performance?
3. How much energy is contributed by various oxidation reactions?
4. How much excess heat is generated during the process?
5. How much heat is transferred from post combustion reaction and by droplets?

METHODOLOGY

The study progresses with the fundamental approach for analyzing the oxygen steelmaking process via mass and energy balances. The developed model is validated with the plant data from Tata steels, the Netherlands. The validation of the model with the industrial results reassures that, in the practical scenario, phosphorus partitioning is not reaching the equilibrium condition. Therefore, equations are formulated to correct the values from Healy’s equation (most commonly used equation to calculate phosphorus partitioning) to the observed industrial phosphorus partition for different blowing technology. This equation is used in the mass balance model to predict realistic values of slag generation.

With the successful development of the comprehensive mass and energy balance model, the research focus to understand the heat flow during the refining period. The dynamic heat flow model is developed by integrating the kinetic models (from the previous studies that predict refining profiles) to the dynamic heat balance calculation to quantify the heat flow contributed by various heat components.

From the understanding of overall heat flow, a global heat transfer model is developed to quantify the heat transfer contributed by different zones (hot spot, hot metal, slag, scrap, droplets) in a BOF converter. In the global model, the droplet heat transfer model is integrated into the overall zone heat balance calculations to predict the temperature evolution profile of hot spot, slag, and hot metal zones during the blowing period.
The in-depth details pertaining to the mass and energy balance model, heat flow model and global droplet heat transfer model developed by the same authors are described in the recent papers [1]–[7].

RESULT AND DISCUSSION

Critical findings from model development studies are discussed below:

**Heat Content in BOF Converter**

![Percentage heat contribution from various exothermic oxidation reactions](image1.png)

The heat balance model prediction shows that sensible heat available from the hot metal is around 66% of total heat input and the rest from the exothermic oxidation reactions. Out of this 34% of the heat from exothermic reactions, between 20% and 25% of heat is evolved from the oxidation of carbon to carbon monoxide and carbon dioxide as shown in Figure 1. With 0.3% to 0.8% of silicon in hot metal, the complete oxidation to silicon oxide contributes around 6% to 10% of the heat input via an exothermic reaction. The model predicts that the oxidation of iron releases around 2% to 4% of the heat during the exothermic reaction.

**Zone Temperature Profile**

![Predicted Hot spot, Slag and Hot metal temperature profiles for a heat loss 3%](image2.png)

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In the global droplet heat transfer model, the heat balance calculations of individual zones (Hot spot, Hot metal bath, Slag) were incorporated and temperature profiles are predicted. The calculations were carried out for a heat loss of 3%. The predicted hot spot temperature profile in Figure 2(a) shows a similar trend to that of industrial measured values a bath heat transfer coefficient value of 33,400 W/m² K.

For slag, the predicted temperature is lower compared to the hot metal temperature during the initial phase of the blow. This is due to the flux dissolution. The slag temperature increase in the later stage is contributed by the increase in hot spot temperature and de-C reaction taking place in the droplet. In addition to that, the post combustion heat transfer through the slag-off gas interface will also heat the slag zone.

With the higher hot spot-hot metal interface area at the initial stage, the predicted hot metal temperature greater than the slag temperature till 5 minutes as shown in Figure 2(b). With the change in lance position the hot spot-hot metal interfacial area decreases resulting the slag temperature to dominate in the next phase of the blow. The current prediction shows that at the end of the blow, the slag temperature (1654°C) was observed to be 8°C greater than the hot metal temperature.

**Excess Heat During BOF Process**

![Figure 3](image)

Figure 3. Overall Excess heat during the blowing period based on profiles of a) Cicutti et al[8], and b) Imphos plant data [9].

The instantaneous overall excess heat calculated from the heat flow model highlights the possibility of optimizing the process. The prediction 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 suggests that there is an increasing trend of excess heat (from 0 to 0.15GJ/min or 0 to 30 MJ/min/t of hot metal) in the second half of the blow.
In the current study, it was observed that the slag generated during the blowing period is mainly heated up by 2 components: (a) Heat transferred by droplets (b) Heat due to post-combustion. Figure 4 quantifies the contribution of heat from the respective components. The droplet heat transfer represents the heat transferred by the droplets to the slag. The heat of the droplet is greater than the slag due to (a) droplets being generated at the hot spot and (b) CO generation during the residence time heat the droplets. The peak of droplet heat transfer is observed to be around 8 minutes. This is due to the fact that de-C reaches a maximum at the same time. During the second half, the droplet heat transfer decreases due to a decrease in de-C rate and residence time. The dip in the droplet heat transfer profile observed at 5 minutes and 7 minutes is due to the change in lance height that influences the droplet generation rate.

The post-combustion heat transfer represents the heat transferred by the post-combustion reaction \( \text{CO} + 0.5\text{O} \rightarrow \text{CO}_2 \) to the slag. This heat component is calculated by assuming (a) that the post combustion heat will heat up the slag (b) CO2 is formed at the same instant at which the de-C takes place. The maximum heat due to post-combustion was also observed to be around 6 minutes. It needs to be highlighted that directing the post-combustion heat to the slag is still a topic for research. However, if technologies can aid in directing higher post-combustion heat (through increased post-combustion ratio) to the slag then the BOF process can retain much heat within the converter.

**Droplet Heat Transfer Efficiency**

**Figure 5.** Overall droplet heat transfer efficiency throughout the blowing period for a heat loss of 3%. [7]
The droplet heat transfer efficiency is defined as the heat transferred by the droplets to the slag to the total heat transferred by droplets (to slag + Hot Metal). Therefore, higher residence time in the 1st half of the blow allows more heat transfer resulting in higher overall droplet heat transfer efficiency as shown in Figure 5. In other words, the effect of slag getting heated up by the droplets will be more than the droplets heating the hot metal. However, near the end of the blow, the droplets heat transfer to the slag drops due to the due to lower residence time of droplets. Therefore, the overall droplet heat transfer efficiency decreases towards the end of the blow.

Overall BOF Heat Loss

![Graph showing the relationship between scrap to hot metal ratio and calculated heat loss percentage.](image)

Figure 6. Heat loss calculation from plant data. R Correlation coefficient.[2]

Considering the plant data from Tata Steel, The Netherlands, the heat loss calculated from the static heat balance model for oxygen steelmaking process ranges from 1.3% to 5.9% of the total heat input. This percentage heat loss is equivalent to 29 MJ/t of hot metal to 130 MJ/t of hot metal. From analyzing the plant data, there is evidence that a linear relation exists between scrap-to-hot metal ratio and heat loss for specified silicon in the hot metal of 0.43% to 0.53%, the carbon in the hot metal of 4.4% to 4.5% and assumed PCR of 0.12.

Effect of Higher Post-Combustion Heat Transfer

![Graph showing the relationship between PCR (%) and scrap percentage along with global warming potential.](image)

Figure 7. Effect of PCR (%) on scrap percentage and global warming potential [6]
The values of PCR measured and calculated from various studies show that typically the PCR value ranges from 10% to 22%. Figure 7 highlights that if we can cross the present industrial limit of PCR % i.e., beyond 22%, then increased PCR% from 22% to 40% will aid in more increased scrap percentage i.e., around ~31% scrap and decreases the GWP from 148 Kg/t of liquid steel to 130 Kg/t of liquid steel. This will in effect increase BOF productivity through improved energy consumption. It needs to be emphasized that various operations are aiming for a higher post-combustion ratio to utilized heat available for more scrap melting but there are engineering challenges associated with implementing this strategy.

CONCLUSIONS

A heat transfer model to simulate the thermal behaviour of the oxygen steelmaking process was developed. The mathematical model is developed with the fundamental approach of (a) static mass and heat balance that helps to understand the overall flow of mass and energy associated with the process, (b) dynamic heat balance that captures the transient heat flow during the process and (c) zone based heat balance that quantifies the heat transfer between different zones. The results obtained from the present study lead to the following conclusions:

- The model predictions enabled to quantify overall heat loss in a oxygen steelmaking process. Analysing the plant data the estimated heat loss in a BOF was found to vary from 1.3% to 5.9% of the total heat input.
- The excess heat profile predicted by the dynamic heat flow model estimates that significant heat is available during the middle of the blow. The excess heat during this period can be minimized by controlling the oxygen flow rate, intermittent feeding of scrap during the blow, optimizing the scrap mix and calculated addition of flux.
- The predicted hot spot temperature profile shows a similar trend to that of industrial result. In case of slag temperature, it was predicted to be lower than the hot metal temperature at the initial phase of the blow and thereafter the slag temperature becomes greater than the hot metal temperature.
- If the BOF is to be developed as scrap melting technology both increased post combustion and preheating of feed will be necessary. Previous work suggests that over 50% scrap feeds are possible (with an expected 40% decrease in GWP) but this will require capital investment in PC and preheating equipment; and close attention to scrap chemistry and sizing leading to a large capital investment overall. However, comparing the energy utilization to EAF steelmaking, the BOF route has some advantages as a scrap melting technology since heat loss from a typical BOF varies from 2% to 8% whereas, in EAF the heat loss varies in the range of 20% to 30%. Therefore, from an environmental perspective, optimizing the chemical energy from the BOF serves for scrap melting is an attractive option.
- The model predictions showed that droplet ejected from the hot spot zone losses temperature to the surrounding. It is estimated that till 10 minutes of the blow, the droplets transfer 90% of the heat of the droplets to the slag, and then this declines towards the end of the blow.

REFERENCES