Analysis of Heat Loss in Oxygen Steelmaking

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST's strategy to become the epicenter for steel's digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.

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Steelmaking is an energy-intensive process and about 20–40% of the steel production cost depends on how effectively the energy is utilized.[1] Therefore, the oxygen steelmaking industry always strives to improve productivity and profitability by addressing the issues pertaining to energy consumption. The total energy requirement and excess heat available from the metallurgical process can be analyzed by conducting a mass and energy balance. Plants rely on in-house process models to calculate the mass and energy consumed before starting the process. However, the details of such models are rarely shared in the open literature.

In the basic oxygen furnace (BOF), the top-blown technology is the most dominant one. To conduct an energy balance for the same, the heat output components considered are heat of steel, heat of slag, heat of scrap melting and heat of flue gases. In addition to that, heat loss or excess heat is another component of heat balance, computed by subtracting the heat of output from the heat of input. Previous studies[2–9] have considered recovering heat from different heat output components to improve the energy efficiency of the process. These were done by (a) effectively utilizing a heat of flue gas, (b) achieving in-furnace post-combustion, (c) heat recovery from slag and (d) energy savings by adjusting scrap to the hot metal ratio in the input feed. These are explained in more detail in the following sections.

Effective Utilizing Heat of Flue Gas — During a typical BOF production cycle, more than 100 m^3 of flue gas per metric ton of steel produced escapes at a temperature ranging from 1,200 to 1,650°C.[4,10] The offgas consists of mainly CO and CO_2 with a post-combustion ratio ranging from 0.10 to 0.22[11–14] and a calorific value of ~6–8 MJ/m^3.[4] Recovery of sensible heat from the offgas improves BOF efficiency and lowers greenhouse gas (GHG) emissions. However, high capital cost is required for recovery retrofitting units and maintenance due to hot gases being dirty.[2–4]

Achieving In-Furnace Post-Combustion — With a lower post-combustion ratio, the CO present in the flue gas has potential energy that can be achieved by completely converting CO to CO_2. Lances designed with secondary oxygen injectors aid in the complete oxidation of CO to CO_2 and release 3.5 times more energy than partial oxidation, which can be utilized for scrap melting.[5,6] It was estimated that with enhanced post-combustion, scrap melting can be increased by 5% and CO_2 can be lowered by 10 kg/t of steel.[4] However, the effectiveness of utilizing post-combustion energy depends on the efficiency of heat transfer from offgas to hot metal bath. In addition to that, higher velocity of the flue gas limits the possibility of in-furnace post-combustion.

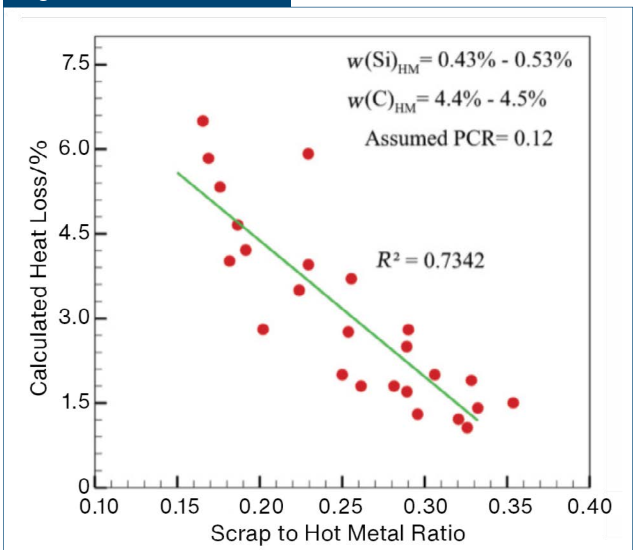
Heat Recovery From Slag — The temperature of the slag generated from the BOF typically ranges from 1,450 to 1,650°C.[15–17] It was approximated that by cooling the slag from 1,550°C, the sensible heat of 0.15 GJ/t of liquid steel can be recovered.[4] However, economically attractive processes are required to achieve sensible heat recovery from the molten slags.[7] In addition to that, the efficiency of sensible heat recovery from slag decreases with temperature. To address this issue, chemical heat recovery (that is applicable less than 430°C) is employed by reacting CaO in slag with CO_2, and the heat released from the exothermic reaction is captured.[7] Therefore, the combination of the sensible and chemical heat recovery process can effectively utilize the heat from the BOF slag.

Energy Savings by Adjusting Scrap to Hot Metal Ratio in the Input Feed — Sensible heat of hot metal contributes the majority of heat input to the BOF plant.[9] The sensible heat of hot metal depends on the chemistry and temperature of the hot metal. Therefore, consistency in the hot metal charge composition and temperature can improve BOF control and optimize energy consumption through a reduction in the need of re-blows.[18] Similarly, decreasing the hot metal and increasing the scrap or direct reduced iron (DRI) at the BOF input was found to be another way to effectively utilize the energy and lower the CO_2 emissions.[8,9]

As mentioned previously, every heat balance will be associated with a heat output component known as heat loss or excess heat. By analyzing 35 heat sets from Tata Steel's 330-metric-ton BOF in the Netherlands, the previous mass and energy balance study[9] conducted by the same authors shows that the heat loss varies from around ~1.2% to ~6.5% of the total heat input which accounts to around 29–130 MJ/t of steel as shown in Fig 1. As this energy is not utilized, it goes as different forms of heat loss such as heat lost through converter walls, heat loss through the mouth, heat of dust, heat taken up by lance cooling water, heat taken up by the mouth scull, heat of bottom gas, heat of formation of solid slag precipitates such as C_2S ($2CaO.SiO_2$), C3P ($3CaO.P_2O_5$), loss on ignition and heat loss during turndown. To the best of the authors' knowledge, no published work has discussed how the heat loss can be controlled and its dependence on various parameters at different operating conditions of the oxygen steelmaking process.

With the mass and energy balance models developed by the authors,[19,20] the heat loss is computed. The details of the balance model are described in recent papers.[9,20] The present study emphasizes the quantification of heat loss available as a function of different operating parameters such as hot metal composition, steel composition, tapping temperature, post-combustion ratio and scrap percentage in the input feed. Furthermore, various possibilities of utilizing and optimizing the heat loss or excess heat available are also discussed, taking industrial scenarios into account.

Figure 1



Heat loss calculation from plant data.[19]

Methodology

In this paper, a model based on static mass and energy balance is used to analyze the excess heat generated during the steelmaking process. The overall balance is conducted by considering the properties and reaction enthalpies of the input and output components from the data available in the literature. In the static mass balance, a series of equations were derived from elemental mass balance and these equations were coupled using distribution equations. The distribution equations used for developing the model are of three types: empirical relations (Eqs. 1 and 2), thermodynamic relations (Eqs. 4 and 5) and equilibrium phase diagram relation (Eqs. 6 and 7). With the iterative loop and associated calculations, the converged solution implies that the mass input (hot metal, scrap, flux + coolant, oxygen, refractory) equals the mass of the product (liquid steel) and byproducts (slag, flue gas, dust + splashes). Further details of the model are described in a recent paper.[20]

$$(\%\ FeO)\ \sqrt{[\%C]} = 4.2 \pm 0.3, \text{ for BOF with C} < 0.1\% \text{ at tap temperature } 1{,}610 \pm 20°C \quad \text{(Eq. 1)}$$

$$\frac{[\%Mn]}{(\%MnO)}\frac{1}{\sqrt{[C]}} = 0.1 \pm 0.02, \text{ for BOF with C} < 0.1\% \text{ at tap temperature } 1{,}610 \pm 20°C \quad \text{(Eq. 2)}$$

$$Lp\frac{(P\%)}{[\%P]}$$

where Lp = phosphorus partition

(Eq. 3)

$$\log Lp = \frac{22350}{T(K)} + 2.5\log(\%Fe) + 0.08(\%CaO) - 16 \pm 0.4$$

(Eq. 4)

Lp industrial = 0.09934 Lp + 30
(top blown)

(Eq. 5)

$(\%MgO_{s,1600}) = 0.23B^4 - 3.16B^3 + 16.4B^2 - 40B + 45.2$
where B = basicity = $(\%CaO)/\%SiO_2$

(Eq. 6)

$$\%MgO_{sat,T(K)} = (\%MgO_{s,1600}) \cdot e^{\left(5.5478 - \frac{10391}{T(K)}\right)}$$

(Eq. 7)

$$PCR = \frac{\%CO_2}{\%CO + \%CO_2}$$

where PCR = post-combustion ratio

(Eq. 8)

With the converged mass balance, the energy balance model computes the different components of heat output (heats of steel, slag, flue gases, heat of scrap melting) and heat input (sensible heat of liquid hot metal and heat of reaction), of which the heat of offgas depends on the post-combustion ratio, which is given by Eq. 8. In the present calculation, the value of the post-combustion ratio is calculated based on the plant data from Tata Steel IJmuiden. With these details, the heat difference between input and output quantifies the overall heat loss (Eq. 9) from the BOF process. Other details pertaining to the formulation, assumptions and calculation of individual heat components are discussed in the heat balance paper.[9] The heat loss is computed to analyze its dependence on each heat component present in the energy balance.

Excess Heat or Heat Loss = (Sensible Heat of Liquid Hot Metal + Heat of Reactions) – (Sensible Heats of Steel + Sensible Heats of Slag + Sensible Heats of Waste Gases + Heat of Scrap Melting)

(Eq. 9)

Excess Heat or Heat Loss = Operational Loss + Additional Heat Available for Scrap Melting

(Eq. 10)

Combining (9) and (10):

Operational Loss + Additional Heat Available for Scrap Melting
= (Sensible Heat of Liquid Hot Metal + Heat of Reactions) – (Sensible Heats of Steel + Sensible Heats of Slag + Sensible Heats of Waste Gases+ Heat of Scrap Melting)

(Eq. 11)

$$\text{Excess Heat or Heat Loss \%} = \frac{\text{Excess Heat or Heat Loss}}{\text{Total Heat Input}} \times 100$$

(Eq. 12)

Total Heat Input = Sensible Heat of Hot Metal + Heat of Reaction

(Eq. 13)

$$\text{Scrap \%} = \frac{\text{Mass of Scrap}}{\text{Mass of Hot Metal + Mass of Scrap}}$$

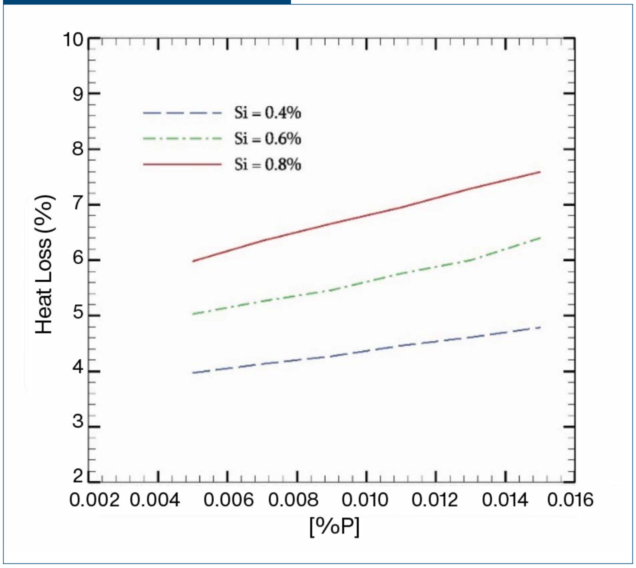
(Eq. 14)

The heat loss comprises operational loss (heat loss through the mouth, converter wall, heat taken up by lance cooling water, bottom blowing gas, heat of formation of solid slag precipitates such as C_2S ($2CaO.SiO_2$), C_3P ($3CaO.P_2O_5$), or undissolved fluxes, heat of dust, or loss on ignition) and additional heat that can be utilized for scrap melting.

Results and Discussion — The developed model was validated against 35 heat data sets from Tata Steel.[19,20] The Tata Steel BOF shop operates a 330-metric-ton-capacity converter integrated with combined blowing technology. Oxygen is delivered through a 6-hole lance at supersonic speed and bottom stirring is achieved via injecting Ar/N_2. Along with the hot metal, fluxes in the form of lime, raw dolomite, burnt dolomite, and coolants such as recycled slag and iron ore, are also added during the blowing period. The details pertaining to the validation were described in other papers.[19, 20]

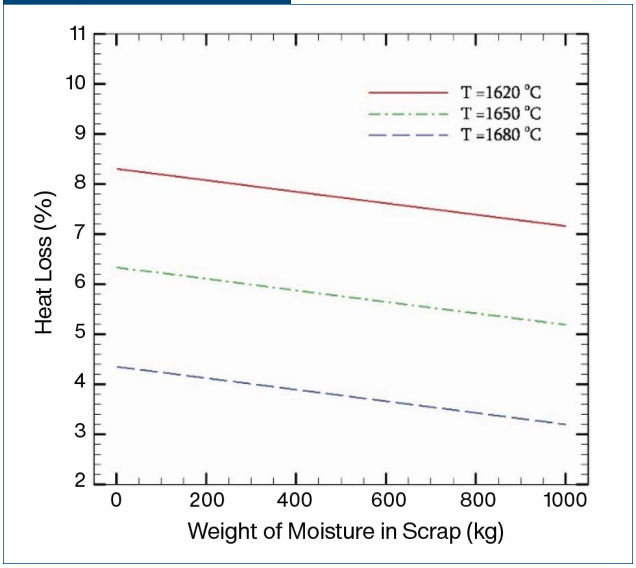
The removal of P from the hot metal plays an important role in determining the amount of flux added or slag to be generated. For a given input hot metal and fixed aim tap temperature, when the required P levels in steel are higher, the amount of

Figure 2



Effect of P in steel on heat loss at different Si levels in hot metal, tapping temperature 1,650°C and P in hot metal 0.06%.

Figure 3



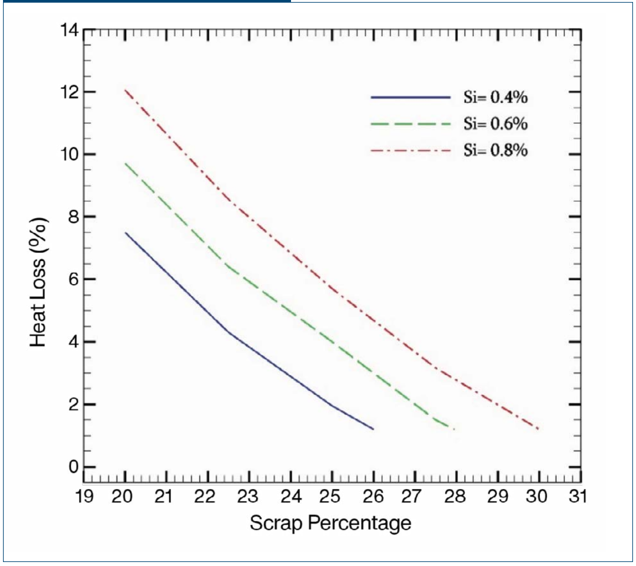
Effect of moisture in scrap on heat loss at different tapping temperatures.

slag generated is low. This implies that the quantity of heat retained by the slag within the converter is low. Therefore, the remaining heat will be accounted as an increase in heat loss, as shown in Fig. 2. Similarly, when the Si level in hot metal is increased, the mass of slag generated increases. However, the heat generated by silicon exothermic oxidation is more than the heat taken up by the increase in the mass of slag (due to more excess Si refined). Therefore, the heat loss was also found to increase by ~1% with the 0.2% increase in Si level, as shown in Fig. 2.

The presence of moisture in the scrap is a parameter that needs to be considered to understand its effect on the heat balance. From the Tata Steel BOF shop, it was reported that the moisture content in the scrap can vary from 1 to 1,000 kg. Considering the weight of moisture in scrap varying from 1 to 1,000 kg as the basis, the trend of heat loss at different tapping temperatures is shown in Fig. 3. With more moisture in the scrap, the heat requirement for vaporizing the moisture will increase, resulting in the effective utilization of heat. Therefore, heat losses are expected to decrease with an increase in moisture content. Similarly, the increased tapping temperature means more slag generation (to prevent P reversal) and more heat will be associated with the slag. Hence, the heat loss is expected to decrease by ~2% with an increase in tapping temperature by 30°C. However, this conclusion needs to be tested with plant data to strengthen the claim. It needs to be acknowledged that heat during the turndown period can be utilized for evaporating the moisture. The current calculation has not considered the turndown heat. Therefore, there exists a possibility that Fig. 3 may be underestimating the heat loss.

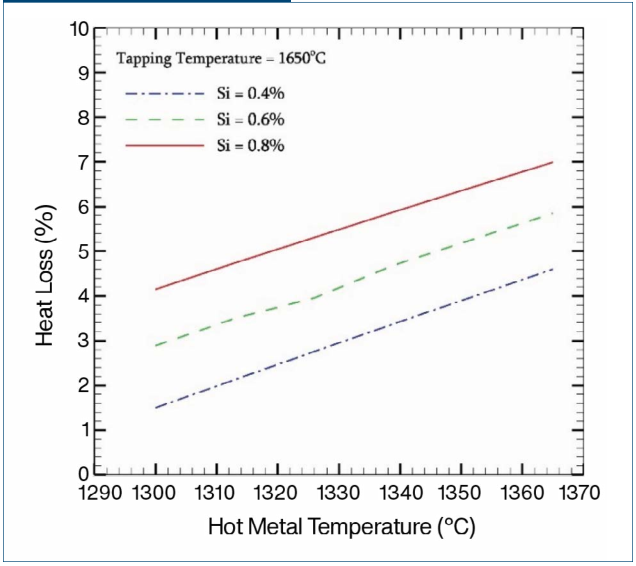
The future of BOF steelmaking depends on how efficiently heat with the system can be utilized by scrap fed into the converter. A recent study[19] describes scrap as a heat sink and Fig. 4 shows that by increasing the scrap percentage, the heat loss can be minimized. On the other hand, the higher percentage of Si in the hot metal increases the heat content (due to exothermic Si oxidation), which facilitates increased scrap

Figure 4



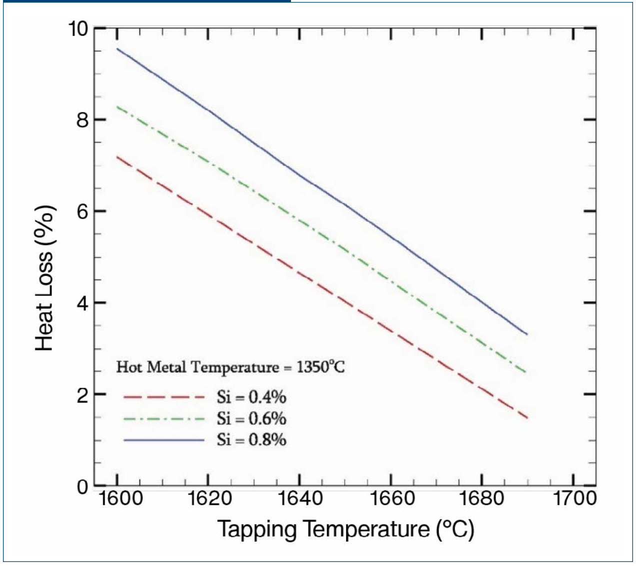
Effect of scrap percentage on heat loss at different levels of Si in hot metal.

Figure 5



Effect of hot metal temperature on heat loss at Si levels of 0.4%, 0.6% and 0.8%.

Figure 6



Effect of tapping temperature on heat loss at Si levels of 0.4%, 0.6% and 0.8%.

melting within the converter. Fig. 4 highlights that by increasing the Si level from 0.4% to 0.8%; the upper limit of scrap quantity ranges from 26% to 30% with a predicted heat loss of ~1.2%.

Considering the range of industrial BOF input and output temperature, influences of hot metal and tapping temperature on the heat loss are plotted as shown in Figs. 5 and 6. Higher hot metal temperature denotes that more heat content is available in the heat input. Therefore, for a fixed tapping temperature, the heat loss was found to increase by ~0.6% for every 10°C rise in hot metal temperature (Fig. 5), whereas when the tapping temperature is increased with fixed hot metal temperature, the thermodynamics of P removal requires increased addition of flux and more slag to be generated. Higher slag volumes mean part of the excess heat is likely to be taken up by the heat of slag, resulting in a decrease in the heat loss. As discussed previously, higher Si content provides more heat through exothermic oxidation. Consequently, the heat losses are expected to increase at higher levels of Si, as shown in Figs. 5 and 6.

The results from the analysis show the relation of heat loss with different operating parameters. The predictions highlight that different possibilities exist to fine-tune the BOF process to achieve better optimization. However, it needs to be acknowledged that the calculations about how heat loss changes with different parameters have not tested rigorously against plant data (except for scrap/metal ratio), so they are really predictions. Therefore, validation of predicted heat loss trend with industrial results will provide more justification for these claims.

Conclusions

The following conclusions can be inferred from the present study:

- The lower level of Si in hot metal and P in steel minimizes the overall excess heat during the process.
- At any tapping temperature ranging from 1,620°C to 1,680°C, when the moisture content is increased from 1 to 1,000 kg and the heat loss, was found to decrease by 1.3%.
- When Si in hot metal is increased level from 0.4% to 0.8%, the upper limit of scrap quantity was found to increase from ~26% to ~30% with a heat loss (operational heat loss) of ~1.2%.
- Keeping the tapping temperature fixed for every 10°C rise in hot metal temperature, the heat loss was found to increase by ~0.6%.

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