ESTIMATING THE TEMPERATURE OF LIQUID STEEL IN BOF STEELMAKING

M.M. LOTFY¹, H.A. AHMED² AND F.A. ELREFAIE³

ABSTRACT
A simple mathematical method is established based on the principles of mass and energy balance, thermodynamics and the kinetics of the oxidation rates to estimate the temperature change of the melt bath during the oxygen blow in BOF (LD converter). An approach was used based on a hypothetical assumption, which is no scrap added to the reactor, as a first step. The amount of scrap could be added at the beginning of the operation, which is calculated from static mass and energy balances, is used in combination with the hypothetical temperature change during the oxygen blown, which is calculated from the dynamic mass and energy balances, to calculate the temperature change during the oxygen blowing time. It is found that the amount of scrap could be added is 232.7 kg/ton hot metal, while the hypothetical temperature of the melt bath reaches 1832.11°C by the end of the blow. The final temperature change of the melt bath is then compared to another which is measured based on full scale experimental work.

KEYWORDS: Temperature, BOF, steelmaking, liquid Steel, oxygen blowing, scrap, mass balance, energy balance.

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1. INTRODUCTION

Although the continuous increase of producing steel by electric arc furnace (EAF), the production of carbon and low alloy steel by oxygen converter process still is the main process. Basic oxygen furnace (BOF) is a liquid – gas reactor in which high carbon hot metal is oxidized and converted to low or medium carbon steel after eliminating the undesired elements. It is a highly complex thermochemical process, which makes the quantitative prediction of thermodynamical functions and states during or at the end of the process a real challenge [1 – 4].

Andersson used a linear regression from TimeAOD2 to predict the temperature of the liquid steel while he was studying the influence of temperature on decarburization using fundamental AOD model. He found that there is a noticeable difference between the temperature predicted by TimeAOD2 model and the linear regression in his study [5].

Fruehan studied the influence of temperature increase on decarburization in basic oxygen furnace (BOF) using argon as the stirring gas. He concluded that the temperature changes did not affect the decarburization significantly and suggested that an average process temperature of 1675°C could be used [6].

DebRoy and Robertson calculated the compositions at different depths in the melt using a model which had been developed by them [7], later they compared the prediction data which they calculated for the refining of the whole converter against experimental heat data and found a good agreement. They used a heat balance to describe the temperature of the process [8].

Wei and Zhu had a series of researches on both side and mixed blown converters to study the influence of the temperature of the process on decarburization implying calculating the temperature increase during the blowing time. Firstly they developed a mathematical model using heat balance to calculate the temperature increase of the process of a side blown converter [9]. Secondly they made an investigation of a reaction model for a combined top and side blown converter and concluded that the temperature
approach used in the side blown converters was not suitable for application on the combined top and side blown converter [10].

A model is developed by Jarvin et al. and Pilsila et al. that simulated the temperature of the liquid steel at each time step [11&12], but the model introduced is similar to that of DebRoy and Roberson [8] and that of Wei and Zhu [9,10].

Ternsted took temperature into consideration, including heat of reactions as well as heat lost in offgas and cooling effects of slag when he was developing a model for time argon – oxygen decarburization converter \{\text{TimeAOD2}\}[13].

Ellahony did many experiments to characterize the LD process at the Egyptian iron and steel company, as a result of his work the temperature change of the melt bath is measured during the oxygen blowing time.[14]

The aim of this work is establishing a simple mathematical method to calculate the temperature change during the BOF steelmaking process based on material and energy balance, the kinetic data available in literature and the thermodynamic data of the process. This leads to estimate the amount of scrap could be added and the rate of oxygen to be blown to operate the reactor at its optimum thermal conditions.

2. CALCULATIONS

The composition and amount of both liquid steel and slag formed at the tapping in BOF depends on the initial composition of input hot metal, the oxidation rates of hot metal constituents, and the additions added to the melt bath. The formed metal oxides transfer to slag while the formed oxides of carbon transfer as a gas phase. The possible oxidation reactions that may happen during the blowing time are shown in reactions (1 – 10) [15]. [_____]: component dissolved in liquid metal phase, (< >): component in slag phase, \{ \}: component in gas phase, and< >: component in solid phase.

\[
[\text{Si}] + \{O_2\} = (\text{SiO}_2)
\]
\[
\begin{align*}
[Mn] + 0.5\{O_2\} &= (MnO) \\
[P] + 1.25\{O_2\} &= 0.5(P_2O_5) \\
[Fe] + 0.5\{O_2\} &= (FeO) \\
[C] + 0.5\{O_2\} &= \{CO\} \\
(MnO) + \text{<C>} &= [Mn] + \{CO\} \\
(FeO) + \text{<C>} &= [Fe] + \{CO\} \\
\{CO\} + 0.5\{O_2\} &= \{CO_2\} \\
\text{<CaO>} + \text{<SiO_2>} &= \text{<CaSiO_3>} \\
3\text{<CaO>} + \{P_2O_5\} &= \text{<Ca_3P_2O_8>} 
\end{align*}
\]

An approach based on a hypothetical assumption which is there is no scrap added to the reactor at the beginning of the operation, consequently the amount of the scrap could be added is calculated from static mass and energy balances while a hypothetical temperature change of the melt bath is estimated from dynamic mass and energy balances. The final temperature change of the melt bath during the oxygen blow is then calculated, as the final step, by using the amount of the scrap could be added and the hypothetical temperature change. The main outlines of the methodology of the work are shown in Fig.1. The kinetics of the oxidation reactions, reduction reactions, the percentage composition of input hot metal and the percentage composition of constituents after blowing time are shown in Figs.2&3. The chemical composition of the input hot metal is shown in Table. 1 [16].
Fig. 1. The main outlines of the methodology used in our work.

Fig. 2. Change in the melt composition during the blow in BOF [16].
Fig. 3. Change in Slag Composition during the blow [16].

Table 1. The chemical composition of the hot metal

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight (kg)/ton Hot Metal</th>
<th>Weight Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>42</td>
<td>4.2</td>
</tr>
<tr>
<td>Si</td>
<td>5.6</td>
<td>0.56</td>
</tr>
<tr>
<td>Mn</td>
<td>7</td>
<td>0.7</td>
</tr>
<tr>
<td>P</td>
<td>1.55</td>
<td>0.155</td>
</tr>
<tr>
<td>S</td>
<td>0.19</td>
<td>0.019</td>
</tr>
<tr>
<td>Fe</td>
<td>943.66</td>
<td>94.366</td>
</tr>
<tr>
<td>Total</td>
<td>1000</td>
<td>100</td>
</tr>
</tbody>
</table>

2.1 Static Calculations

2.1.1 Static mass balance

Static mass balance calculations are carried out by applying the general equation Eq. (11)[17], on every constituent in the hot metal to estimate both of the mass and composition of all streams at the end of the blow, also to calculate the stoichiometric weight of oxygen that should be injected. All the calculations are based on one ton hot metal input with the composition shown in table.
the oxidation rates shown in Figs. 2&3. Eqs. (12 –15) and (30– 34) are deduced from applying Eq. (11) on the input and output streams.

\[
(mass \ input) + (mass \ generated) = (mass \ output) + (mass \ destroyed) \\
+ (mass \ accumulated)
\]

(11)

2.1.1.1 Estimating the weight and composition of liquid steel

The weight and composition of liquid steel, at the end of the oxygen blow, are calculated by applying Eq. (12) on each constituent.

\[
W_M(st) = W_M(h) - W_M(oxi) - W_M(off) + W_M(add)
\]

(12)

2.1.1.2 Estimating the weight and composition of molten slag

The weight and composition of molten slag, at the end of the oxygen blow, are calculated by applying Eq. (13) on each constituent. The dolomitic lime is practically added at the beginning of the blow time. The lime to silica ratio is assumed to be four to achieve an appropriate basic slag during the blow, also wt. % of MgO in slag is assumed to be seven to saturate the slag and consequently retard dissolution of the furnace refractories [16].

\[
W_{MxOy(sl)} = W_{M(oxi)}/(x*M.WtM)*M.Wt_{MxOy} + W_{MxOy(add)} - W_{MxOy(off)}
\]

(13)

2.1.1.3 Estimating the weight and composition of offgas

The weight and composition of offgas, at the end of the oxygen blow, are calculated by applying Eq. (14) on carbon, assuming that all the carbon oxidized produces carbon monoxide. On the other hand, carbon monoxide is produced from the reduction reactions of both of iron oxide and manganese oxide by carbon as shown in reactions (6 & 7). The weights of carbon oxidized and manganese oxide reduced are deduced from Fig.1 while the weight of iron oxide reduced is deduced from Fig. 2. According to the equilibrium oxygen pressure of Fe oxidation inside the reactor about 10% of the volume of carbon
monoxide will be oxidized to carbon dioxide [18], which is calculated by applying Eq. (15).

\[ W_{CO_{(off)}} = \frac{W_{C_{(oxi)}}}{M.Wt_c} \times M.Wt_{CO} \]  

(14)

\[ W_{CO_{2_{(off)}}} = 0.1 \times \frac{W_{CO_{(off)}}}{M.Wt_{CO} \times M.Wt_{CO_{2}}} \]  

(15)

### 2.1.2 Static energy balance

The only source of heat input in BOF {LD converter} is the chemical energy which is in the form of the heat liberated from the oxidation of the hot metal constituents by the injected oxygen, through the lances, and heat of slag formation. On the other hand the heat supplied to the furnace is consumed in heating the hot metal, formed slag, lime added, offgas, and the injected oxygen to the exit temperature.

Energy balance calculations are carried out on the BOF {LD converter} steelmaking process using the hot metal with the composition shown in Table.1 and the values calculated from the static mass balance calculations. The general form of general balance equation, Eq. (16) is applied on all input and output streams to estimate the total heat input and the sensible heat of each output stream. Eqs. (17– 24) and (35) are deduced from applying Eq. (16) on the input and output streams.

The reference temperature is taken as the temperature of input hot metal which was 1343°C. All the heats of oxidation reactions and heat capacities at constant pressure \( C_p \) are assumed to be constant and independent on temperature [18]. All thermodynamical data are taken from Ref. [16].

\[ \sum_{i=1}^{k} Wi (dHi) = 0.0 \]  

(16)

#### 2.1.2.1 Calculating the total heat input

The total heat input is calculated by applying Eqs. (17 – 19) on reactions (1 – 10) using values which were previously calculated by means of mass balance calculations at the end of the blow.
\[ \Delta H^\circ \text{(react)} = W_{\text{Si(oxi)}} \cdot \Delta H^\circ \text{(react)(Si)} + W_{\text{Mn(oxi)}} \cdot \Delta H^\circ \text{(react)(Mn)} + W_{\text{C(oxi)}} \cdot \Delta H^\circ \text{(react)(C)} + W_{\text{P(oxi)}} \cdot \Delta H^\circ \text{(react)(P)} + W_{\text{Fe(oxi)}} \cdot \Delta H^\circ \text{(react)(Fe)} + W_{\text{MnO(red)}} \cdot \Delta H^\circ \text{(red)(6)} + W_{\text{FeO(red)}} \cdot \Delta H^\circ \text{(red)(7)} + W_{\text{CO}_2\text{(off)}} \cdot \Delta H^\circ \text{(8)} \] (17)

\[ \Delta H^\circ \text{(sl)} = W_{\text{SiO}_2\text{(sl)}} \cdot \Delta H^\circ \text{(9)} + W_{\text{P}_2\text{O}_5\text{(sl)}} \cdot \Delta H^\circ \text{(10)} \] (18)

\[ \Delta H^\circ \text{in} = (\Delta H^\circ \text{(react)} + \Delta H^\circ \text{(sl)}) \] (19)

2.1.2.2 Calculating the sensible heat of liquid steel and molten slag

The sensible heat of liquid steel and molten slag is calculated by applying Eqs. (20 – 24) using values, which were previously calculated by means of mass balance calculations, at the end of the blow.

\[ \Delta H^\circ \text{in} + \Delta H^\circ \text{out} + \Delta H^\circ \text{loss} = 0.0 \] (20)

\[ \Delta H^\circ \text{(lime)} = \Delta H^\circ \text{MgO (heating)} + \Delta H^\circ \text{CaO (heating)} \] (21)

\[ \Delta H^\circ \text{(off)} = W_{\text{CO (off)}} \cdot \Delta H^\circ \text{CO (off)} + W_{\text{CO}_2\text{(off)}} \cdot \Delta H^\circ \text{CO}_2\text{(off)} \] (22)

\[ \Delta H^\circ \text{(O}_2\text{)} = W_{\text{O}_2} \cdot \Delta H^\circ \text{(O}_2\text{) (heating)} \] (23)

\[ \Delta H^\circ \text{(st)} + \Delta H^\circ \text{(sl)} = \Delta H^\circ \text{out} - (\Delta H^\circ \text{(off)} + \Delta H^\circ \text{(lime)} + \Delta H^\circ \text{(O}_2\text{)}) \] (24)

2.1.3 Calculating the Weight of Scrap that could be added

The calculated sensible heat of steel and slag would result in increasing the temperature of liquid steel and slag. The temperature at the end of oxygen blowing is calculated by applying Eqs. (25 & 26).

\[ \Delta T_{\text{(hyp)end}} = \left( \Delta H^\circ \text{(st)} + \Delta H^\circ \text{(sl)} \right) / \left( C_p \text{(st)} \cdot W \text{(st)} + C_p \text{(sl)} \cdot W \text{(sl)} \right) \] (25)

\[ T_{\text{(hyp)end}} = T_{\text{(in)}} + \Delta T_{\text{(hyp)end}} \] (26)

The temperature of liquid steel at the end of oxygen blowing is larger than the tapping temperature, so there is a temperature difference which yields an unused sensible heat which could be reduced and profited in the same time to melt an added amount of scrap. The temperature difference and sensible heat could be reduced are calculated by applying...
Eqs. (27&28) respectively while the amount of scrap could be added is calculated by applying Eq. (29)

\[ \Delta T_{\text{red}} = T_{\text{hyp end}} - T_{\text{tap}} \]  
\[ \Delta H_{\text{red}} = \Delta T_{\text{red}} \cdot (C_P \cdot W_{\text{st}} + C_P \cdot W_{\text{sl}}) \]  
\[ W_{\text{scr}} = \frac{\Delta H_{\text{red}}}{(C_P \cdot (T_{\text{tap}} - 25))} \]

2.2 Dynamic Calculations

2.2.1 Dynamic mass balance

The composition change, during the blow in BOF steelmaking, of hot metal, molten slag produced, and offgas produced should be calculated at first by applying Eqs. (30 – 34) on the reactions (1 – 7) using the kinetics plotted in Figs. (1&2).

\[ W_{M\text{(oxi) } t\%} = \mu \cdot W_{\text{in}} \]  
\[ W_{MxOy\text{ (sl) } t\%} = \frac{W_{M\text{(oxi) } t\%}}{(x \cdot M \cdot Wt_{M})} \cdot M \cdot Wt_{MxOy} + W_{MxOy\text{ (add)}} \]  
\[ W_{M(h) t\%} = (1 - \mu) \cdot W_{\text{in}} \]  
\[ W_{CO\text{(off) } t\%} = \frac{W_{C\text{(oxi) } t\%}}{M \cdot Wt_{C} \cdot M \cdot Wt_{CO}} \]  
\[ W_{CO2\text{(off) } t\%} = 0.1 \cdot W_{CO\text{(off) } t\%} \cdot M \cdot Wt_{CO} \cdot M \cdot Wt_{CO2} \]

2.2.2 Dynamic energy balance

Dynamic energy balance calculations are carried out by applying Eqs. (17–24) on all the streams after every 5% of the oxygen blowing time using the values calculated by dynamic mass balance in the previous section.

2.2.3 The hypothetical temperature change of the liquid steel

The temperature difference of the liquid bath is calculated after every 5% of the blowing time by applying Eq. (35) from the beginning of the oxygen blowing to the half of the oxygen blowing time while Eq. (36) is applied from the half to the end of the
blowing time, the temperature of the liquid bath is then calculated by applying Eq. (37) using the values calculated from Eq. (35) and (36).

\[
\Delta T_{\text{(hyp)}} = \frac{(\Delta H_{\text{ho}}(t\%) + \Delta H_{\text{sl}}(t\%))}{(C_{P(h)} \cdot W_{(h)t\%} + C_{P(sl)} \cdot W_{(sl)t\%})}
\]

\[
\Delta T_{\text{(hyp)}} = \frac{(\Delta H_{\text{ho}}(st)t\% + \Delta H_{\text{sl}}(st)t\%)}{(C_{P(st)} \cdot W_{(st)t\%} + C_{P(sl)} \cdot W_{(sl)t\%})}
\]

\[
T_{\text{(hyp)t\%}} = T_{in} + \Delta T_{\text{(hyp)t\%}}
\]

2.2.3 The final temperature change of the liquid steel considering the scrap effect

The temperature of the liquid steel is recalculated with taking in consideration the scrap cooling effect from the beginning of the oxygen blowing time to the end. The correlated temperature is calculated after every 5% of the blowing by applying Eqs. (38–40) using the previously calculated values of the weight of hot metal/liquid steel, the weight of molten slag, the temperature of the liquid bath calculated from Eq. (37) after t% of the blowing time and the calculated amount of scrap could be added. Eq. (38) is applied from the beginning of the oxygen blowing to the half of the oxygen blowing time while Eq. (39) is applied from the half to the end of the blowing time.

\[
W_{t\%}^* = \frac{(W_{(h)t\%}) \cdot C_{P(h)} + W_{(sl)t\%}) \cdot C_{P(sl)}}{(W_{scr} \cdot C_{P(scr)})}
\]

\[
W_{t\%}^* = \frac{(W_{st(t\%}) \cdot C_{P(st)} + W_{sl(t\%}) \cdot C_{P(sl)}}{(W_{scr} \cdot C_{P(scr)})}
\]

\[
T_{st(f)t\%} = \frac{(W_{t\%}^* \cdot T_{\text{(hyp)}} + 25)}{(W_{t\%}^* + 1)}
\]

3. RESULTS AND DISCUSSION

3.1 Mass Balance

The weights and compositions of liquid steel, molten slag and offgas at the end of the oxygen blow are shown in Tables. 2 – 4. The high weight of iron in the produced liquid steel is due to the fact that the scrap added is assumed to be pure iron.
Table 2. The Composition of Liquid Steel Produced after adding Scrap.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight (kg)</th>
<th>Weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>1151</td>
<td>99.71</td>
</tr>
<tr>
<td>C</td>
<td>0.34</td>
<td>0.03</td>
</tr>
<tr>
<td>Mn</td>
<td>2.75</td>
<td>0.24</td>
</tr>
<tr>
<td>P</td>
<td>0.10</td>
<td>0.009</td>
</tr>
<tr>
<td>S</td>
<td>0.19</td>
<td>0.016</td>
</tr>
<tr>
<td>Total</td>
<td>1154.38</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3. The Weight and Composition of Slag formed at the end of The Oxygen Blow.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Weight (kg)</th>
<th>Weight percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>48</td>
<td>43.8</td>
</tr>
<tr>
<td>SiO₂</td>
<td>12.53</td>
<td>11.43</td>
</tr>
<tr>
<td>MgO</td>
<td>7.67</td>
<td>7</td>
</tr>
<tr>
<td>FeO</td>
<td>32.6</td>
<td>29.74</td>
</tr>
<tr>
<td>MnO</td>
<td>5.47</td>
<td>5</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>3.32</td>
<td>3.03</td>
</tr>
<tr>
<td>Total</td>
<td>109.59</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4. The composition of Offgas at the end of the Oxygen Blow.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Weight (kg)</th>
<th>Weight percentage</th>
<th>Volume (Nm³)</th>
<th>Volume percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>87.48</td>
<td>90.93</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td>CO₂</td>
<td>15.27</td>
<td>9.07</td>
<td>7.78</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>102.75</td>
<td>100</td>
<td>77.78</td>
<td>100</td>
</tr>
</tbody>
</table>
The change of the weight of slag during the oxygen blow is shown in Fig. 4. The sharp increase in the weight of the slag at the beginning of the first quarter till 17.5% of the oxygen blowing time is due to the oxidation of all silicon content and the dolomitic lime added besides the calcium silicate slag is assumed to be formed, see reaction (9), at the first 5% of the blowing time. The slight drop of the weight of the slag from 17.5% to 50% of the blow time is due to the reduction of iron oxide from 8.2% to 30% and the reduction of manganese oxide from 25% to 50% of the blowing time according to reactions (6&7), which means that the reduced iron and manganese revert to the metal. After the reduction period ends the oxidation of both of iron and manganese will proceed which explains the increase of the weight of the slag again till the end of the oxygen blow.

The change of the weight of hot metal / liquid steel during the oxygen blow is shown in Fig. 5. The slight decrease from 17.5% to 50% of the blowing time is due to the reversion of iron and manganese to hot metal but in the same time the carbon oxidation proceeds. The rate of carbon oxidation is slightly larger than the reductions rates of both of iron oxide and manganese oxide thus the decrease of the hot metal weight continues while the weight of carbon monoxide increases for the same reason as shown in Fig. 6. It is observed from dynamic mass balance calculations that the percentage of carbon in hot metal reaches to about 2% at 50% of the blowing time and continues decreasing as long
as the oxygen blowing proceeds thus the beginning of the formation of liquid steel is at the middle of the blowing time according to the iron–carbon phase diagram.

Fig. 5. The Change of the Weights of both Hot Metal and Liquid Steel, before Scrap Addition, during the oxygen blow.

Fig. 6. The change of the mass of CO and CO₂ in the offgas during the oxygen blow.

The change of the weight of oxygen required for oxidation reactions is shown in Figs. 7&8. It is obvious that most of oxygen required is for oxidizing carbon content as shown in Fig.8, while the weight of oxygen required for oxidizing other hot metal constituents is minor.
Fig. 7. The Change of the weight of oxygen required to oxidize elements contented in Hot Metal during the oxygen blow.

Fig. 8. The weight of oxygen required for C oxidation and the Total weight of Oxygen required for all of the oxidation reactions during the oxygen blow.

3.2 Energy Balance

3.2.1 Heat input

The total heat liberated due to oxidation reactions is 809.46 MJ/ ton hot metal. The main source of input heat is the heat of oxidation of C, produced about 48.8% of the total
heat input, while the second one is the heat of oxidation of Si, produced about 20.81% of the total heat input, although its small content in hot metal relative to C. Although the heat of reaction of phosphorus oxidation is relatively large but its low content in hot metal makes its participation to the total heat input is the lowest, as shown in Fig. 9. The total heat liberated due to slag formation is 56.84 MJ/ton hot metal. The heat liberated due to oxidation reactions introduces about 93.44% of the total heat input which makes it the main source for heat in basic oxygen furnace (BOF). The total heat input to the basic oxygen furnace is 866.3 MJ/ton hot metal. The heat liberated due to slag formation introduces 6.56% of the total heat input as shown in Fig. 10.

Fig. 9. The Change of Heats liberated due to Oxidation reaction during the oxygen blow.

Fig. 10. The Change of heat liberated due to slag formation, summation of heat liberated due to oxidation reactions and the total heat input during the oxygen blow.
3.2.2 Heat output

The heat consumed in heating the produced CO and CO$_2$ by the end of the blowing time is 162.7 and 29 MJ/ton hot metal respectively. The sensible heat of offgas by the end of the blowing time are 191.72 MJ/ton hot metal. The heat consumed in heating lime added and the injected oxygen are 126.34 to BOF is 69.8 MJ/ton hot metal respectively. The total heat loss is 387.86 MJ/ton of hot metal. Heat transfer loss is ignored in calculations. The heat lost in raising the temperature of offgas occupies the first place in heat loses. It represents 49.43% of the total heat lose, while the heat lost in raising the injected oxygen occupies the second place by 32.57% of the heat lose. The total heat loss represents about 44.77% of the total heat input as shown in Fig. 11.

![Graph showing heat losses](image)

Fig. 11. The Change of Heat losses and The Total heat Losses during the oxygen blow

3.2.3 The sensible heat of steel and slag

The values of the sensible heat of liquid steel and slag during the oxygen blow are shown in and Fig.12. The sensible heat of steel and slag reaches to 478.44 MJ/ton hot metal at the end of the oxygen blow which represents 55.23% of the total heat input.
Fig. 12. The change of sensible heat of Hot metal/ Liquid Steel during the oxygen blow.

3.2.4 The temperature of liquid steel and the weight of scrap requirements

The hypothetical temperature change of melt bath reaches to 1832.11°C by the end of the blowing time. An amount of scrap could be added to the reactor before the oxygen blowing to reduce the temperature of liquid steel and increase the yield of metallic iron. The amount of scrap could be added is calculated based on the temperature difference between the hypothetical temperature of liquid steel as if there is no scrap added and the tapping temperature. The amount of scrap could be added to the reactor at the beginning of the converting operation is 232.72 kg/ ton hot metal and it is considered as pure iron.

Practically the scrap is charged into the empty reactor at the room temperature, the hot metal is then poured ,after that the oxygen blowing starts, so the final temperature of the hot metal/liquid steel is less than the calculated hypothetical temperature due to the scrap cooling effect which is due to heating , allotropic transformation, phase transformation and dissolution. The hypothetical temperature change of the melt bath, no scrap added, versus the calculated actual temperature change, considering the addition of the scrap from the beginning of the operation, are shown in Fig.13. The sharp difference between the calculated final and hypothetical temperatures at the first 5% of the oxygen blowing time, shown in Fig.13, is due to the large temperature difference between the cold scrap, at the room temperature, added to the reactor and the temperature of the hot metal which
has been poured at 1343°C, then the temperature of the melt bath increases due to the heat liberated due to the oxidation reactions.

Fig. 13. The calculated hypothetical and actual temperature change during the oxygen blow.

The final calculated temperature change of the melt bath is compared to a full scale experimentally measured temperature change of the melt bath during the oxygen blow[14] and a good verification with an error not more than ±5% as shown in Fig. 14.

Fig. 14. The calculated actual temperature change versus the full scale measured temperature change during the oxygen blow.
It is obvious that there is a difference between the initial calculated and measured temperatures, before the starting of the oxygen blow, that is due to that the initial measured temperature was that of both of the hot metal and scrap as a mixture while the initial temperature used in our calculations is taken as the temperature of the hot metal only. The calculated temperature is larger than the measured one between 10% and 30% of the oxygen blow time which may be due to the effect of size of scrap and extent of mixing within the phases and between the phases.

The calculated temperature is less than the measured one between 30% and 50% of the oxygen blowing time may be due to the reduction rates of manganese and iron oxides in this period according to the kinetics used in our calculations and the different oxygen flow rate used in the full scale experimental measurements and the calculated one used in our calculations. There is a good agreement between the calculated and measured temperatures in the last half of the oxygen blowing time as shown in Fig. 14.

4. CONCLUSION

A simple mathematical method is established based on the principles of mass and energy balance, thermodynamics and the kinetics of the oxidation rates to estimate the actual temperature change during the oxygen blow in BOF (LD converter). An approach has been used based on a hypothetical assumption that there was no scrap added to the reactor. The mount of scrap could be added at the beginning of the operation, which is calculated from static mass and energy balances, is used in combination with the hypothetical temperature change during the oxygen blown, which was calculated from the dynamic mass and energy balances, to calculate the actual temperature change during the oxygen blowing time.

The major source of the heat input is the exothermic heats of the oxidation reactions of the hot metal constituents especially carbon. The sensible heat of steel and slag reaches to 478.44 MJ/ ton hot metal at the end of the oxygen blow. The sensible heat of steel and slag represents 55.23% of the total heat input. The temperature of liquid steel reaches to
1832.11°C by the end of the blowing time. The calculated amount of scrap could be added is 232.7 kg/ton hot metal and it is considered as pure iron. The scrap added before the start of the oxygen blowing would cause a sharp drop at the first 5% of the blowing time then the temperature would increase again due to the proceeding the oxygen blow. The actual calculated temperature change during the oxygen blowing time is compared to the temperature change based on full scale experimental measurements and a good agreement with an error not more than ±5% is found.

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REFERENCES

### List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Symbol</th>
<th>Meaning</th>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>st</td>
<td>Steel</td>
<td>T</td>
<td>Temperature (°C)</td>
<td>add</td>
<td>Additions to BOF</td>
</tr>
<tr>
<td>sl</td>
<td>Slag</td>
<td>$M_xO_y$</td>
<td>The oxide of element M</td>
<td>M.Wt</td>
<td>The molecular weight</td>
</tr>
<tr>
<td>h</td>
<td>Hot metal</td>
<td>oxi</td>
<td>oxidized</td>
<td>M</td>
<td>Element M</td>
</tr>
<tr>
<td>off</td>
<td>Offgas</td>
<td>scr</td>
<td>scrap</td>
<td>W</td>
<td>Weight (kg)</td>
</tr>
<tr>
<td>t%</td>
<td>Time percentage of blowing</td>
<td>$\mu$</td>
<td>Fraction of element M oxidized</td>
<td>$\Delta H^o_{\text{react}}(M)$</td>
<td>Heat of oxidation of M (MJ/kg M)</td>
</tr>
<tr>
<td>$C_P$</td>
<td>Heat Capacity at constant pressure</td>
<td>$\Delta T_{\text{(red)}}$</td>
<td>Temp.(°C) Difference should be reduced</td>
<td>$\Delta H_{\text{(red)}}$</td>
<td>Amount of Heat should be removed from the bath (MJ)</td>
</tr>
<tr>
<td>V</td>
<td>Volume (Nm$^3$)</td>
<td>$\Delta H^o_{(R)}$</td>
<td>Heat of Reaction (R) (MJ)</td>
<td>loss</td>
<td>losses</td>
</tr>
<tr>
<td>$T_{\text{(tap)}}$</td>
<td>Tapping Temp. (°C)</td>
<td>$\Delta T$</td>
<td>Temperature Difference (°C)</td>
<td>$\Delta H^o_{(s)}$</td>
<td>Sensible Heat (MJ)</td>
</tr>
<tr>
<td>$Q_{t%}$</td>
<td>Any Quantity Calculated after t% of the Blowing</td>
<td>hyp</td>
<td>Hypothetical</td>
<td>f</td>
<td>Final</td>
</tr>
</tbody>
</table>

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حساب درجة حرارة الصلب المنصهر خلال انتاج الصلب باستخدام المحولات الأكسجينية

يهدف البحث إلى حساب درجة حرارة المعدن الساخن و الصلب المتكون منذ بداية نفخ الأكسجين من أعلى الفرن وحتى نهاية نفخ الأكسجين. يتم استخدام مبدأ توازن المادة والطاقة ومعدلات تفاعلات الأكسدة التي تحدث داخل المفاعل لأستنتاج كمية الطاقة التي تستهلك في تسخين الصلب و الخبث المتكونين أثناء عملية نفخ الأكسجين. و بناء عليه تم حساب درجة حرارة الخبث و الصلب أثناء الأنتاج والتي تزيد عن درجة حرارة معدن الساخن و بناء على حالات تحسين كمية الخردل في الصب و التغييرات في معدلات حرارة الخبث و الصلب. يتم استخدام كمية الخردل المحسوبة لحساب الدرجة الحرارية داخل المفاعل والذي يعتمد على التغييرات في درجة حرارة الخبث و الصلب لحساب التغيير الحقيقي لدرجات الحرارة داخل المفاعل. وتتم مقارنته بالتغيرات المقاسة عمليا سابقا خلال انتاج الصلب في المحولات الأكسجينية على نطاق الصناعي.