Evaluation of Low-Reducible Sinter in Blast Furnace Technology by Mathematical Model Developed at Centre ENET, VŠB – Technical University of Ostrava

S. Jursova, P. Pustejovska, S. Brozova, J. Bilik

Abstract—The paper deals with possibilities of interpretation of iron ore reducibility tests. It presents a mathematical model developed at Centre ENET, VŠB – Technical University of Ostrava, Czech Republic for an evaluation of metallurgical material of blast furnace feedstock such as iron ore, sinter or pellets. According to the data from the test, the model predicts its usage in blast furnace technology and its effects on production parameters of shaft aggregate. At the beginning, the paper sums up the general concept and experience in mathematical modelling of iron ore reduction. It presents basic equation for the calculation and the main parts of the mathematical model, prediction of iron ore reduction.

The material balance on the individual oxides inside the cylinder of an elementary height is formulated as a transient scheme: [9], [10]

\[ G_i(z + \Delta z) - G_i(z) + G_i(z)^{-1}(z) = M_i(t + \Delta t) - M_i(t) \frac{M_i(t)}{\Delta t} \]  

where the input and output flow rates and the accumulation of Fe in the i-th form are given by the following equations

\[ G_i = \rho_p \cdot C_i \cdot v_p \]  

\[ M_i = \rho_p \cdot C_i (1 - e) \cdot \Delta z \]

In (2) is \( G_{0,1} - G_{4,5} = 0 \).

Fig. 1 Model scheme of counter-current of gas and feedstock [8]

Oxygen balance

\[ n_{FeO} \cdot FeO_{3} \rightarrow Fe_{3}O_{4} \rightarrow Fe_{O} \rightarrow Fe \]  

The iron oxides \( Fe_{2}O_{3} \), \( Fe_{3}O_{4} \) are reduced according the scheme: [9], [10]

The general conception of the mathematical model of reduction is derived for a counter-current reactor in where solids (ore, sinter or pellets) descend and reducing gases ascend. The reactor is represented by a cylinder where the burden and the reducing gas move in plug flow. The coordinate axis \( z \) is parallel to the axis of the cylinder. The reducing gas enters at the bottom at \( z=0 \) and the solid charge enters at the top with at \( z=L \). [8]
The reduction rates are given by:
\[ G_{i,i+1} = \rho_p R_i C_i (X - X_{r,i})(1 - \varepsilon) \Delta z \] (5)

The solution is completed by the set of the partial differential equations to be solved for given initial and boundary conditions. [11], [12]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_i )</td>
<td>Fe concentration in the ( i )th form as the fraction of the entire amount of Fe in the charge</td>
<td>%</td>
</tr>
<tr>
<td>( sol )</td>
<td>flow rate of Fe in the ( s )th form into the cylinder</td>
<td>kmol ( m^2 ) s(^{-1} )</td>
</tr>
<tr>
<td>( M_i )</td>
<td>accumulation of Fe in the form ( i ) in the elementary cylinder</td>
<td>kmol m(^{-3} )</td>
</tr>
<tr>
<td>( G_{i,i+1} )</td>
<td>amount of Fe in the form ( i ) reduced to Fe in the form ( i+1 )</td>
<td>kmol m(^{-2} ) s(^{-1} )</td>
</tr>
<tr>
<td>( \nu_i )</td>
<td>speed of descent of the burden</td>
<td>m s(^{-1} )</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>void fraction</td>
<td></td>
</tr>
<tr>
<td>( \rho_p )</td>
<td>the total content of Fe in the ore burden</td>
<td>kmol m(^{-3} )</td>
</tr>
</tbody>
</table>

Carbon monoxide, CO, as the reducing agent passes through the burden to be gradually oxidized to CO\(_2\). Regeneration of CO\(_2\) to CO in contact with solid carbon is not considered in the model. In the blast furnace we are thus concerned with reduction in the isothermal zone where the rate of the reaction CO\(_2\) + C = 2CO under the prevailing temperature is so slow that it can be ignored. [13], [14]

II. EXPERIMENT

The results of reducibility tests were used as input data for the model and blast furnace technology interpretation. The reducibility tests were carried out with samples of sinter used in a Czech metallurgical plant for pig iron production. In Table II there is a chemical analysis of the material. [15], [16]

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Analysis of Tested Sinter</th>
<th>%</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeO(_{total})</td>
<td>56.15</td>
<td>FeO</td>
<td>10.06</td>
</tr>
<tr>
<td>Mn</td>
<td>0.36</td>
<td>Fe(_2)O(_3)</td>
<td>69.10</td>
</tr>
<tr>
<td>S</td>
<td>0.014</td>
<td>Zn</td>
<td>0.016</td>
</tr>
<tr>
<td>Cr</td>
<td>0.041</td>
<td>K(_2)O</td>
<td>0.020</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>9.06</td>
<td>TiO(_2)</td>
<td>0.043</td>
</tr>
<tr>
<td>CaO</td>
<td>8.66</td>
<td>P(_2)O(_5)</td>
<td>0.11</td>
</tr>
<tr>
<td>MgO</td>
<td>1.13</td>
<td>C</td>
<td>0.07</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>1.05</td>
<td>basicity</td>
<td>0.91</td>
</tr>
</tbody>
</table>

The laboratory test was carried out in a stationary fix bed in the retort under the conditions in Table III.

| Sample weight | 500 g |
| Sample grain size | 10-12.5 mm |
| Temperature | 950 °C |
| Reduction gas | 60 % NO\(_2\), 40 % CO |
| Equilibrium concentration | \( X_{e,1} = 0.01, X_{e,2} = 0.198, X_{e,3} = 0.675 \) |

The experimental method was based on mass loss resulted from oxygen elimination from iron oxide. [17] The reduction process is depicted in Fig. 2. There is presented loss mass in time of the experiment.

Fig. 2 The mass loss of the sample during the reducibility test

The final reducibility index \( dR/dt \) was calculated according to standard ISO 4695. The index is expressed at molar ration O/Fe = 0.9 % as [18]:
\[
\frac{dR}{dt} \left( \frac{O}{Fe} = 0.9 \right) = \frac{33.6}{t_{30} - t_{60}}
\] (6)

where \( t_{30} \) is time to attain a degree of reduction of 30%, [min]; \( t_{60} \) is time to attain a degree of reduction of 60%, [min]; 33.6 is a constant

The degree of reduction \( R_t \), relative to the iron(III), after \( t \) min, as follows:
\[
R_t = \left( \frac{0.111w_1}{0.430w_2} + \frac{m_3 - m_t}{m_0 \cdot 0.430w_2} \cdot 100 \right) \cdot 100
\] (7)

where \( m_0 \) is the mass of the test portion [g]; \( m_3 \) is the mass of the test portion immediately before starting the reduction [g]; \( m_t \) is the mass of the test portion after reduction time \( t \) [g]; \( w_1 \) is the iron(II) oxide content of the test sample prior to the test [%]; \( w_2 \) is the total iron content of the test portion prior to the test [%].

The equation is derived in terms when the total oxygen in iron oxides is in the form of hematite (Fe\(_2\)O\(_3\)) while in the most of iron ores there is a portion of magnetite (Fe\(_3\)O\(_4\)), wüstit (FeO) and metalized Fe. Therefore the degree of reduction is calculated from mass loss of the sample during the reduction plus the difference between theoretical content of oxygen in the prior sample which is in Fe\(_2\)O\(_3\), Fe\(_3\)O\(_4\) and FeO oxides.

Table IV presents results of the test such as reducibility index \( dR/dt \) and kinetic constants calculated at void fraction 0.4 mm. The tested sinter with \( dR/dt \) 0.72 is typical of low reducibility. The pig iron production with this material relates to higher coke consumption. The sinter usage in production is further evaluated. The interpretation is focused on its effect on reduction gas consumption and direct reduction rate.
TABLE IV
RESULTS OF REDUCIBILITY TEST

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>dR/dt</td>
<td>0.72</td>
</tr>
<tr>
<td>void fraction Ɛ</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>kinetic constant K₁</td>
<td>0.01014</td>
</tr>
<tr>
<td>kinetic constant K₂</td>
<td>0.00404</td>
</tr>
<tr>
<td>kinetic constant K₃</td>
<td>0.00055</td>
</tr>
</tbody>
</table>

III. DISCUSSION

The result of kinetic model is an interpretation of changes in the concentration of substances in the shaft aggregate during the reduction. Fig. 3 presents the changes in oxidation grade of ore feedstock and in gas. At the same time, it brings information about changes in concentration of oxides during the descent of the feedstock through the area of non-direct reduction in the blast furnace.

For possible industrial optimization, there was predicted the reduction of the tested sinter typical of low reducibility with well reducible one. For model situation a highly basic sinter of reducibility index dR/dt = 1.13 was used. Reduction process of FeO of low reducible sinter with well reducible one is presented in Fig. 4. The intersection of FeO trend with the vertical surface of relative height of non-direct reduction area (defining the end of non-direct reduction) presents the ration of FeO left for the direct reduction.

It is obvious that the lowest coke consumption is in the optimal rate between direct and non-direct reduction. A different ratio results in an increase of coke consumption. The model interpretation has to respect the real dynamics of blast furnace technology. The productivity of blast furnace aggregate is affected by feedstock descent. The rate effects on the time of feedstock stay in the area of non-direct reduction. The shorter time results in the increase in ratio of direct reduction and the increase of heat demand relating to coke consumption. An optimizing area for the specific consumption of reduction gas, relating to the time of stay in non-direct reduction area and direct reduction rate is depicted Fig. 5. In case of well-reducible sinter usage, the optimizing area for the specific consumption of reduction relating to the time is typical with lower ratio of direct reduction and for optimized blast furnace feedstock processing in the zone of non-direct reduction rate is required shorter time. The comparison is obvious from Fig. 6.

Fig. 3 Reduction of iron oxides and changes in oxidation of tested sinter

Fig. 4 Non-direct reduction of FeO at various ratio of low reducible sinter with well reducible one

Fig. 5 Relation among the specific consumption of reduction gas, time of non-direct reduction and direct reduction rate for low reducible sinter

Fig. 6 Comparison of optimizing area of relation between process well reducible sinter

Fig. 7 presents the time effect of feedstock stay in the area of non-direct reduction. It presents the changes in limit kinetic curves of carbon consumption at time of feedstock stay in the area of non-direct reduction. As the time is shorter, the limit kinetic curve of carbon consumption is of higher values.
IV. CONCLUSIONS

The paper presented a model developed at Centre ENET, VSB – Technical University. The model of non-direct reduction in the blast furnace is possible to use for calculation at various conditions of non-direct reduction process such as various specific reduction gas consumption or productivity of the technology. It is possible to use the model for calculation of relation between specific carbon consumption and rate of direct reduction index.

In the paper was simulated reduction process of low reducible sinter. The kinetic constants describing changes in iron oxide concentration was:

\[ k_1 = 0.01014 \text{ for transformation of } \text{Fe}_3\text{O}_4 \text{ to } \text{Fe}_2\text{O}_3 \]
\[ k_2 = 0.00404 \text{ for transformation from } \text{Fe}_3\text{O}_4 \text{ to } \text{FeO}_{1.05} \]
\[ k_3 = 0.00055 \text{ for describing changes } \text{FeO}_{1.05} \text{ to } \text{Fe} \]

Also, there were graphically presented changes in iron oxides concentration. As the oxidation of blast furnace feedstock (X) decreases, the gas is enriched by the oxygen and oxidation grade (Y) is being increased.

Finally, there was presented an optimizing area for reduction of low-reducible sinter in comparison with optimized reduction of well reducible one. It is completed by simulation of reduction gas consumption at different time of sinter processing in non-direct reduction zone.

ACKNOWLEDGMENT

This paper has been elaborated in the framework of the project New creative teams in priorities of scientific research, reg. no. CZ.1.07/2.3.00/30.0055, supported by Operational Programme Education for Competitiveness and co-financed by the European Social Fund and the state budget of the Czech Republic.

REFERENCES


Simona Jursova was born in Czech Republic, 1984. In 2011 she obtained her Ph.D. degree in Environmental Protection in Industry. Her dissertation was focused on industry of metallurgy, especially metallurgical waste and its recycling in production cycle. Nowadays she works as a junior researcher at Centre ENET – Energy Units for Utilization of non-Traditional Energy Sources founded at VSB – Technical University of Ostrava in 2010. Her main research interest is research on reducibility of iron ores. She is a co-author of Czech monograph Modelling, Analysis and Prediction of processes for pig iron production in the view of current energy and ecological conditions and has cooperated in many research notes and papers published in international journal such as, Metallurgist, Chemical and Process Engineering, Acta Megallurgica Slovaca, Steel Research.