

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

S. Jursová, P. Pustějovská, S. Brožová, J. Bilík

Abstract—The paper deals with possibilities of interpretation of iron ore reducibility tests. It presents a mathematical model developed at Centre ENET, VSB – 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 developed model. In the experimental part, there is an example of usage of the mathematical model. The paper describes the usage of data for some predictive calculation. There are presented material, method of carried test of iron ore reducibility. Then there are graphically interpreted effects of used material on carbon consumption, rate of direct reduction and the whole reduction process.

Keywords—Blast furnace technology, iron ore reduction, mathematical model, prediction of iron ore reduction.

I. INTRODUCTION

THE kinetic studies of reduction processes in blast furnace [1]–[6] prove that these processes are determined by many factors such as reduction gas consumption, its temperature, size of feedstock reactive surface, diffusion and properties of used iron ore relating to its origin. At Centre Enet, VSB Technical University of Ostrava, a model for interpretation of iron ore reducibility test was developed. The interpretation presents the laboratory process of reduction and determines its most important phases in relation with genetic differences of used iron ore. The model serves for evaluation of blast furnace technology and its optimization.

The mathematical model designed at Enet, VSB – Technical University of Ostrava includes three parts – a mathematical model of reduction under counter current flow, simulation of iron ore reduction at the fix bed and calculation of specific carbon consumption in blast furnace. The model

works with results of laboratory tests simulating reduction in the fixed bed. The model is able to specify production parameters for the proper ores. [7]

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]

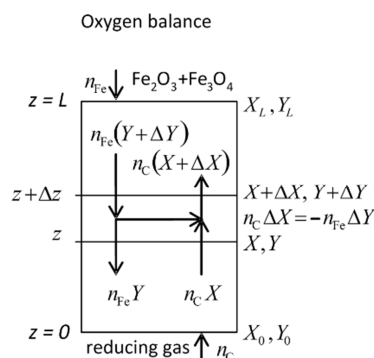
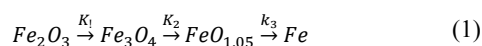


Fig. 1 Model scheme of counter-current of gas and feedstock [8]

The iron oxides Fe_2O_3 Fe_3O_4 are reduced according to the scheme: [9], [10]



The material balance on the individual oxides inside the cylinder of an elementary height is formulated as a transient process by following equation. The nomenclature is summed up in Table I:

$$G_i(z + \Delta z) - G_i(z) + G_{i-1,i}^*(z) = M_i(t + \Delta t) - M_i(t) \frac{M_i(t)}{\Delta t} \quad (2)$$

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

$$G_i = \rho_p \cdot C_i \cdot v_p \quad (3)$$

$$M_i = \rho_p \cdot C_i (1 - \varepsilon) \cdot \Delta z \quad (4)$$

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

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The reduction rates are given by:

$$G_{i,i+1} = \rho_p k_i C_j (X - X_{r,j}) (1 - \varepsilon) \Delta z \quad (5)$$

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

TABLE I
NOMENCLATURE

Symbol	Quantity	SI
C_i	Fe concentration in the i^{th} form as the fraction of the entire amount of Fe in the charge	%
G_i	flow rate of Fe in the i^{th} form into the elementary cylinder	$\text{kmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
M_i	accumulation of Fe in the form i in the elementary cylinder of the Δz height	$\text{kmol} \cdot \text{m}^{-2}$
$G_{i,i+1}$	amount of Fe in the form of i reduced to Fe in the form of $i+1$	$\text{kmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$
v_p	speed of descent of the burden	$\text{m} \cdot \text{s}^{-1}$
ε	void fraction	-
ρ_p	the total content of Fe in the ore burden	$\text{kmol} \cdot \text{m}^{-3}$

Carbon monoxide, CO, as the reducing agent passes through the burden to be gradually oxidized to CO₂. Regeneration of CO₂ 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 $\text{CO}_2 + \text{C} = 2\text{CO}$ 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 II
CHEMICAL ANALYSIS OF TESTED SINTER

	%		%
Fe _{total}	56.15	FeO	10.06
Mn	0.36	Fe ₂ O ₃	69.10
S	0.014	Zn	0.016
Cr	0.041	K ₂ O	0.020
SiO ₂	9.06	TiO ₂	0.043
CaO	8.66	P ₂ O ₅	0.11
MgO	1.13	C	0.07
Al ₂ O ₃	1.05	basicity	0.91

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

TABLE III
CONDITIONS OF THE TEST

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.

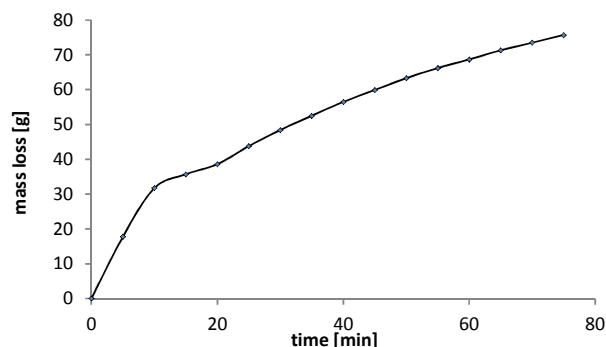


Fig. 2 The mass loss of the sample during the reducibility test

The final reducibility index dR/dt was calculated according to standard ISO 4695. The index is expressed at molar ration $\text{O/Fe} = 0.9$ % as [18]:

$$\frac{dR}{dt} \left(\frac{\text{O}}{\text{Fe}} = 0.9 \right) = \frac{33.6}{t_{60} - t_{30}} \quad (6)$$

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:

$$R_t = \left(\frac{0.111w_1}{0.430w_2} + \frac{m_1 - m_t}{m_0 \cdot 0.430w_2} \cdot 100 \right) \cdot 100 \quad (7)$$

where m_0 is the mass of the test portion [g]; m_1 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 (Fe₂O₃) while in the most of iron ores there is a portion of magnetite (Fe₃O₄), wüstite (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 Fe₂O₃, Fe₃O₄ 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	
dR/dt	0.72
void fraction ϵ	0.4 mm
kinetic constant K_1	0.01014
kinetic constant K_2	0.00404
kinetic constant K_3	0.00055

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.

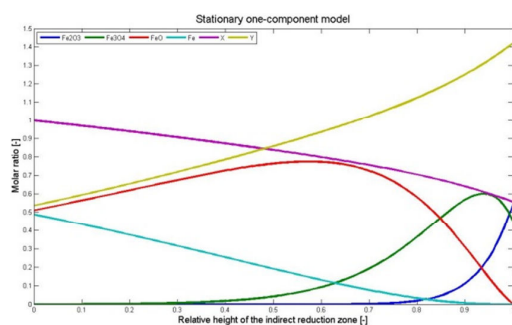


Fig. 3 Reduction of iron oxides and changes in oxidation of tested sinter

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.

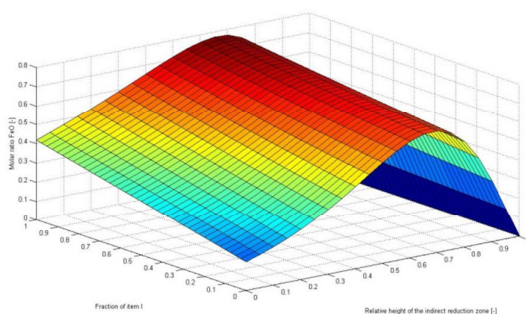


Fig. 4 Non-direct reduction of FeO at various ratio of low reducible sinter with well reducible one

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.

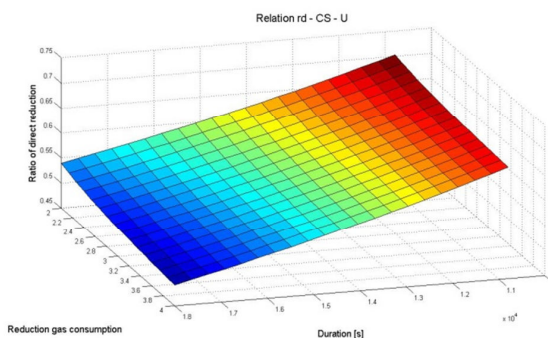


Fig. 5 Relation among the specific consumption of reduction gas, time of non-direct reduction and direct reduction rate for low reducible sinter

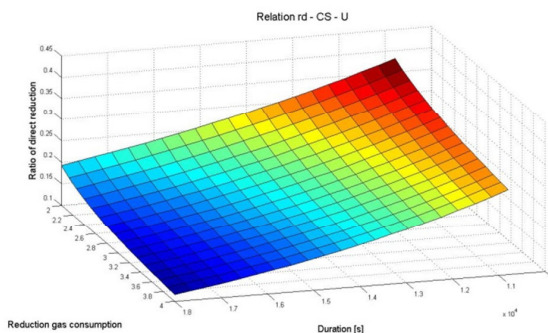


Fig. 6 Comparison of optimizing area of relation between process well reducible sinter

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.

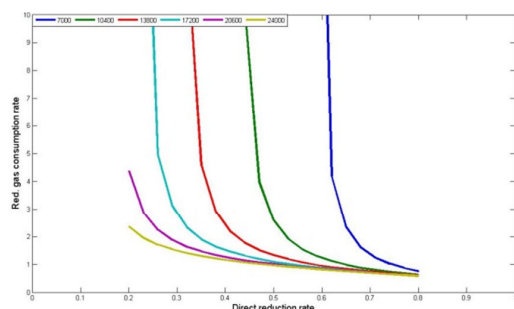


Fig. 7 Relation between reduction gas consumption on direct reduction grade at various times of stay in the area of non-direct reduction

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:

$$k_1 = 0.01014 \text{ for transformation of } \text{Fe}_2\text{O}_3 \text{ to } \text{Fe}_3\text{O}_4,$$

$$k_2 = 0.00404 \text{ for transformation from } \text{Fe}_3\text{O}_4 \text{ to } \text{FeO}_{1,05}$$

$$k_3 = 0.00055 \text{ for describing changes } \text{FeO}_{1,05} \text{ to } \text{Fe}.$$

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.

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