Mathematical Modeling and Simulation in Matlab/Simulink of Processes from Iron Ore Sintering Plants

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Abstract: - This work presents the mathematic models of the basic processes from an iron ore processing plant. Based on the mathematic models, using the Matlab/Simulink platform, it was achieved the simulation of the dosing process and simulation of the sintering process. The achieved mathematic model allows the determination of the material flows in the charge at their chemical composition variation, or at the variation of the reference values of the parameters S, I, r_0, c_0. Further the simulation, there are obtained the time-variations of the optimal speed for the sintering machine at different distributions of iron ore's temperatures on the sintering band.

Key-Words: - Sintering process**,** Sintering plant, Iron ores, Charge, Agglomerate, Sintering machine, Modeling, Simulation, Simulink

1 Introduction

Restructuring of metallurgical industry is strongly influenced by the modernization of manufacturing processes from the sintering plants.

Sintering, as physical-chemical process of iron ores preparation and obtaining of a controlled situation, is of maximum importance because the resulted agglomerate allows the obtaining of quality cast-irons as they are required currently on the market [1,2].

In this respect, the major cast-iron producing countries are using iron ores previously prepared as agglomerate, meant to ensure the achievement of some charges with high iron content and homogeneous from chemical and grading viewpoint.

From the processes with special influence on preparation, in this work are analyzed: dosing, sintering and cooling (fig.1). Dosing flow includes the quantitative dosing of the charge components, their pre-homogenization into the primary mixing drum (TAP) and the conveying flow of the mixture/blend from the dosing station into the main body to the charge bunker of the sintering machine.

Materials extraction from the dosing station's bunkers and their further dosing is achieved by means of dozers with extracting belt. These are mounted in the bunker's entry and they extract the material from the bunker at the flow required by the charge recipe [3,4].

The mixture, which is formed in accordance with the calculated recipe, is collected by the conveyor belts and transported to the TAP primary mixing station. During the process, to the dosed mixture is added further the hot return brought by the metallic belts to the return bunker.

From the TAP, which has an inclination of $2 – 3^0$, the charge mixture is overflowed on the conveyors and the transport is continued on other two conveyor belts towards the main section of the sintering plant from the charge bunker. Sintering flow includes the following steps: mixing/blending, humectation and forming of micro-pellets in the secondary mixing drum (TAS); loading the mixture on the sintering machine's carriers; burning-up the charge; sintering of the mixture/blend; sizing of the agglomerate and recirculation of the return [5,6]. The material from the charge bunker is extracted by a gravimetric dozer with extracting belt, and loaded further in the secondary mixing drum. Inside the TAS, the material is brought to the necessary humidity for the sintering process (7-10%), by adding water.

The humid material, homogenized and micro-palletized in TAS, is loaded on the sintering machine, uniformly on the entire machine's surface, by an oscillating belt. Repartition of the protection bed on the sintering machine's grills should be made in a uniform layer on the entire width of the machine.

The height of the layer on the sintering machine is adjusted by changing the position of the shield against the machine's grills and is established depending on the material's gas permeability.

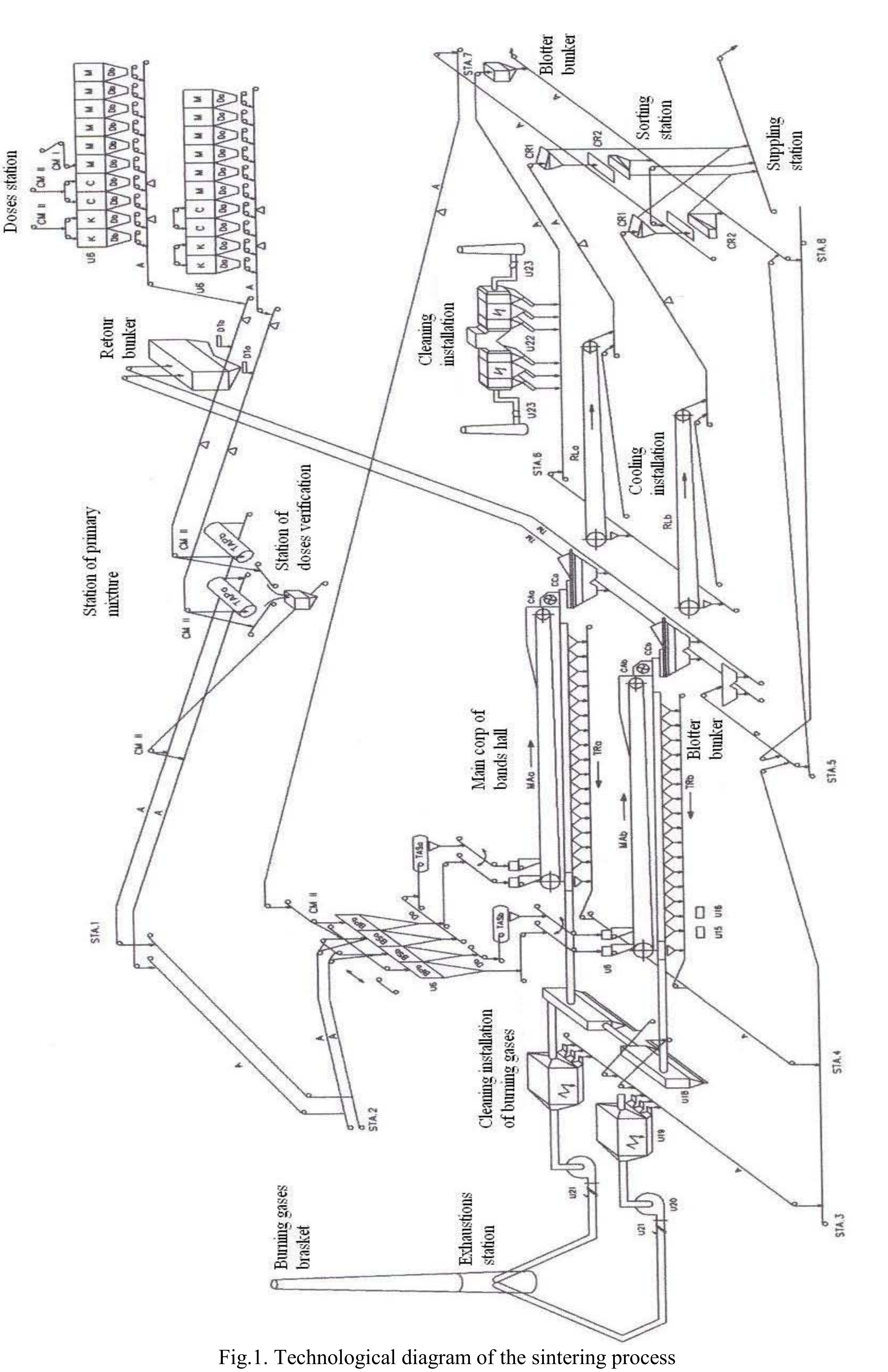

Fig.1. Technological diagram of the sintering process

Cooling flow includes the following steps: cooling of the agglomerate after the hot screening; conveying in cold condition to the screening station; conveying to the furnaces silos and to the agglomerate's shipment station [4].

Cooling of the agglomerate is made on two linear coolers, one for each sintering machine. The cooling air is supplied by 5 fans with an air flow of 200000 m^3/h, blow by each fan. At the entrance on the cooler, the agglomerate has a temperature of 700-800^{0}C and leaves the cooler with 80-100^{0}C, fact which allows it to be transported by some special rubber belts. Each cooling machine is served by an auxiliary belts flow, with the role to collect and convey the material which is returning on the inferior line of the linear cooler and the one which falls under the cooling machines [4,7,8].

2 Modeling the Sub-Processes from an Iron Ore Sintering Plant

In the dosing process from the sintering plants will be taken into account the following conditions:

- the materials supplied for sintering are wet;
- the supplied material quantities are bigger by about 0.5%, percents which represent the losses from manipulation $m_a\,\%$;
- if M is the quantity of wet material (iron ore) that should reach to dosing, the quantity M_a of supplied material is:

$$M_a = \frac{M}{(1 - m_a)} \quad (1)$$

where $m_a = \frac{m_a\%}{100}$; (2)

- the quality of the dosed materials is given in anhydrous condition (dry), therefore, to determine the account of iron, basic oxides and acid oxides, is taken as basis the dry material. Having $w\%$ the humidity percent, the calculation with wet materials will be made by bringing them to the dry condition. The dry iron ore will be: $M_{uscat} = (1 - w) \cdot M$ (3)

where $w = \frac{w\%}{100}$; (4)

- the dosed charge is formed by the total of wet iron ores which are taken as unit or 100% and against which are reported the other additions: coke, limestone, return, as percentages against the total iron ores, or as proportion against the total iron ores, these being also in wet condition;
- a part of the iron ores, before reaching the sintering plant, are passed through the raw materials preparation sector, where are mixed and homogenized, having as result the iron ore mixture called currently "homogenized" which has the deviations at Fe, SiO_2, CaO within the limits of ±0.5%. This homogenized is dosed separately as a self-sustained component;
- by the sintering process, the materials are calcinated and, knowing the calcination percent "$p\%$", the quantity of material found in agglomerate will be:

$$A_i = (1 - w_i) \cdot M_i \cdot (1 - p_i) \quad (5)$$

where $p_i = \frac{p_i\%}{100}$ i = 1,2,. . ., n; (6)

- the coke C_i , after burning, participates in the agglomerate by its ash. For each coke C_i knowing the ash $Ce_i\%$, it results the account of ash in the agglomerate:

$$Ce = \sum_{i=1}^{n} \left(1 - w_{C_i}\right) \cdot C_i \cdot Ce_i \quad (7)$$

- the quantity of coke and return is reported to the total iron ore charge $M = \sum_{i=1}^{n} M_i$ (8)
- the total coke quantity is $C = \sum_{i=1}^{n} C_i$ (9)

$$c_0 = \frac{C}{M} = \sum_{i=1}^{n} \frac{C_i}{M} = \sum_{i=1}^{n} c_i \quad (10)$$

$$\Rightarrow \begin{cases} C_i = c_i \cdot M \\ C = M \cdot \sum_{i=1}^{n} c_i = M \cdot c_0 \end{cases} \quad (11)$$

- the total ash quantity is:

$$Ce = M \cdot \sum_{i=1}^{n} \left(1 - w_{C_i}\right) \cdot c_i \cdot Ce_i \quad (12)$$

- the return results: from the hot screening, having $w_{r_1} = 0$ (R_1); from the cold screening, having $w_{r_2} = 0$ (R_2) and from the screening from the blast-furnace's day-shift bunkers, which is wet for not causing dust $w_{r_3} = 0 \div 1\%$ (R_3);
- for all three types of return will be considered $w_r = 0$, and the total return is:

$$R = R_1 + R_2 + R_3 \quad (13)$$

$$r_0 = \frac{R}{M} = \frac{R_1 + R_2 + R_3}{M} \quad (14)$$

where: R_1 does not pass through dosing, but is discharged on the conveyor belt from the dosing's downstream and R_2 and R_3 are dosed through the dosing bunkers.

The limestone quantity is not dosed by a given average ratio, but determined by the need of basic oxides account, so that in the agglomerate's participation assembly the sum of basic oxides reported to the sum of acid oxides to be in a prescribed ratio, called basicity index I.

$$I = \frac{\sum_{i=1}^{n}(CaO + MgO)}{\sum_{i=1}^{n}(SiO_2 + Al_2O_3)} \tag{15}$$

The dosed iron ores charge is (400 ÷ 500) t/h at daily productions of (8000 ÷ 10000) tons of agglomerate/day. The ratio between the quantity of the produced agglomerate and the iron ore charge is sensitively around value 1, because at basicity I = 1.2 ÷ 1.4 as are prescribed the iron ores' calcination losses, they are compensated by the participation of limestone into agglomerate plus the coke's ash, the return having a null effect, because it's a constant quantity that recirculates (∑outputs = ∑inputs).

The mathematic model of the dosing sub-process is described by the following equations:

$$K = M \cdot \frac{N}{(k_k - Is_k)} \tag{16}$$

$$S = M + K + C + R \tag{17}$$

$$M = S \cdot \frac{1}{1 + c_0 + r_0 + \frac{N}{(k_k - Is_k)}} \tag{18}$$

$$K = S \cdot \frac{\frac{N}{(k_k - Is_k)}}{1 + c_0 + r_0 + \frac{N}{(k_k - Is_k)}} \tag{19}$$

$$R = S \cdot \frac{r_0}{1 + r_0 + c_0 + \frac{N}{(k_k - Is_k)}} \tag{20}$$

$$C = S \cdot \frac{c_0}{1 + r_0 + c_0 + \frac{N}{(k_k - Is_k)}} \tag{21}$$

where:

$$N = \sum_{i=1}^{n} m_i \cdot (Is_i - k_i) + \left[c_0 \cdot Ce \cdot (Is_{Ce} - k_{Ce}) + r_0 \cdot (Is_r - k_r)\right] \tag{22}$$

$$s_i = \sum (SiO_2 + Al_2O_3)_i \tag{23}$$

$$s_{Ce} = \sum (SiO_2 + Al_2O_3)_{Ce} \tag{24}$$

$$s_r = \sum (SiO_2 + Al_2O_3)_r \tag{25}$$

$$s_k = \sum (SiO_2 + Al_2O_3)_k \tag{26}$$

$$k_i = \sum (CaO + MgO)_i \tag{27}$$

$$k_{Ce} = \sum (CaO + MgO)_{Ce} \tag{28}$$

$$k_r = \sum (CaO + MgO)_r \tag{29}$$

$$k_k = \sum (CaO + MgO)_k \tag{30}$$

In the above equations:

M – represents the iron ore flow; K – limestone flow; R – return flow; C – coke flow; S – charge flow; I – basicity index; s_i , k_i – lime and silica from the iron ores ; s_k , k_k – lime and silica from the limestone ; s_{Ce} , k_{Ce} – lime and silica from the coke ashes; s_r , k_r – lime and silica from the return; r_0 – the return participation against the total iron ore ; c_0 – the coke participation against the total iron ore.

In case when is taken into account the humidity of the charge components, we have the following mathematic model:

$$K = M \cdot \frac{N'}{(k_k - Is_k)} \tag{31}$$

$$M = S \cdot \frac{1}{1 + c_0 + r_0 + \frac{N'}{(k_k - Is_k)}} \tag{32}$$

$$K = S \cdot \frac{\frac{N'}{(k_k - Is_k)}}{1 + c_0 + r_0 + \frac{N'}{(k_k - Is_k)}} \tag{33}$$

$$R = S \cdot \frac{r_0}{1 + r_0 + c_0 + \frac{N'}{(k_k - Is_k)}} \tag{34}$$

$$C = S \cdot \frac{c_0}{1 + r_0 + c_0 + \frac{N'}{(k_k - Is_k)}} \tag{35}$$

where:

$$N' = \sum_{i=1}^{n} (1 - w_i) \cdot m_i \cdot (Is_i - k_i) + \left[(1 - w_{c0}) \cdot c_0 \cdot Ce(Is_{Ce} - k_{Ce}) + r_0 \cdot (Is_r - k_r)\right] \tag{36}$$

Maximization of the good-quality agglomerate production is based on the optimization of the sintering machine's speed. The mathematic model contains equations for calculating the necessary corrections for the value of the sintering machine's speed, respectively for the carbon quantity in the charge, by which is adjusted the quantity of the produced ore fines.

Optimization of the sintering machine's speed v_m is based on the coincidence principle of the longitudinal sintering front's length L_a with the machine's working length L_u.

The mathematic model of the sintering sub-process is described by the following equations:

$$v_{m\ opt} = v_m \cdot \frac{L_u}{L_{n-1} + 0{,}5 \cdot p_c \cdot \frac{T_{n-2} - T_n}{T_{n-2} - 2T_{n-1} + T_n}} \tag{37}$$

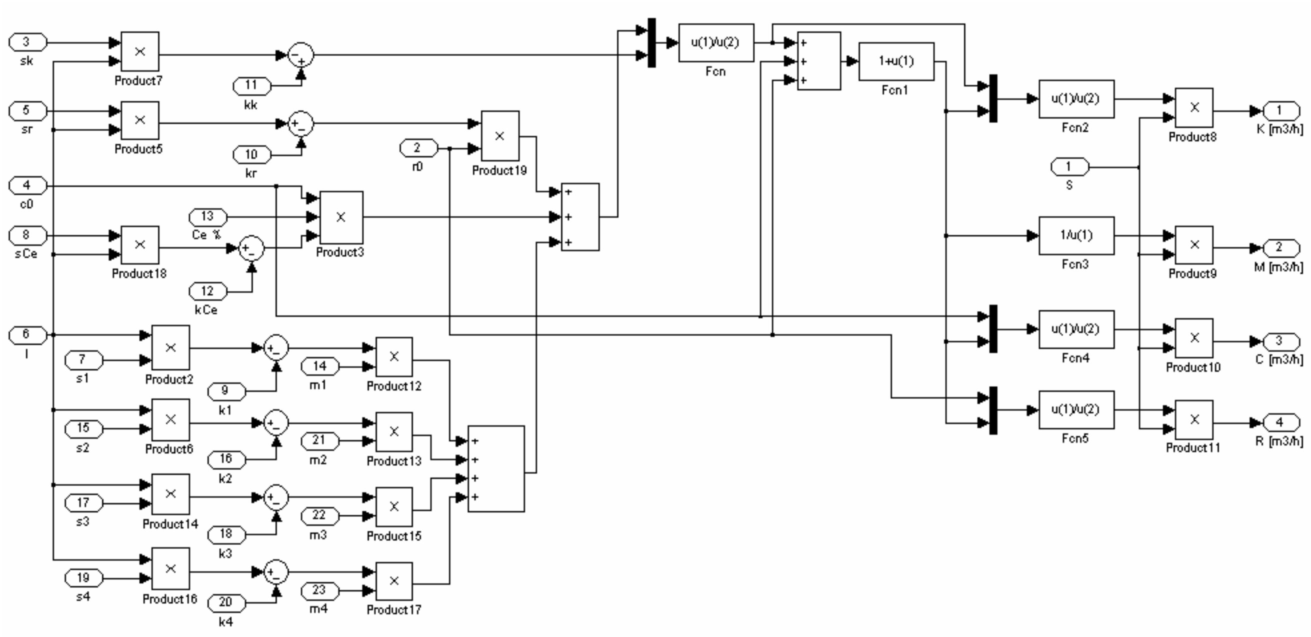

Fig.2. Block diagram for calculation of the material flows from the charge

$$\Delta v_m = v_m \cdot \left(\frac{L_u}{L_{n-1} + 0{,}5 \cdot p_c \cdot \dfrac{T_{n-2} - T_n}{T_{n-2} - 2T_{n-1} + T_n}} - 1 \right) \quad (38)$$

$$\Delta C = 1.25 \cdot \Delta c \cdot M \quad (39)$$

$$\Delta c = \left(a - b \cdot r_0\right) - \left(a - b \cdot r\right) \quad (40)$$

$$S = k \cdot v_{m\ opt} \cdot H_s \cdot B \quad (41)$$

$$v_{m\ min} = \frac{L_u}{H_s} \cdot w_{min} \cdot 10^{-3}\ \text{[m/min]} \quad (42)$$

$$v_{m\ max} = \frac{L_u}{H_s} \cdot w_{max} \cdot 10^{-3}\ \text{[m/min]} \quad (43)$$

$$t_a = \frac{L_u}{v_{med}} = \frac{H_s}{w_{med}} = 10 \ldots 20\ \text{[min]} \quad (44)$$

$$Q_{at} = B \cdot H_s \cdot \left(1 - c\right) \cdot \eta_a \cdot \rho_v \cdot v_{med} \cdot 60\ \text{[t/h]} \quad (45)$$

$\rho_v = 1.6$ [t/m^3]; $\eta_a = 0.93 \ldots 0.96$; $c = 0.06 \ldots 0.13$.

In the above equations intervene the following quantities : v_m – sintering machine's prescribed speed; H_s – layer's height (0.4 m); k – proportionality factor (1.7); B – sintering machine's width (3 m); Δv_m - sintering machine's speed correction, T_n, T_{n-1}, T_{n-2} – temperatures in the last three suction chambers; $r = R/M$ - proportion of the return against the total iron ore; $r_0 = R_{mp}/M$ - proportion of the fine-grained produced against the total iron ore; a, b – constants which are determined statistically for each installation in part; w – speed agglomeration in layer; t_a – agglomeration time; Q_{at} – total agglomeration flow; ρ_v – sinter density; η_a – agglomeration yield [9,10].

3 Simulations in Matlab/Simulink of Sub-Processes from an Iron Ore Sintering Plant

Based on the mathematic model and using the Simulink program from Matlab environment, were executed the diagrams that achieve the simulation of the dosing sub-process of the sintering ores, as well as the simulation of the iron ores' sintering sub-process [4,11]. The subsystem from fig. 2 makes the calculation of the material flow that compose the sintering charge, e.g.: the iron ore flow, limestone flow, coke flow and the return flow considering that in the agglomerate's manufacturing recipe enter four types of iron ore : Romanian iron ore (iron ore 1), Krivoi-Rog iron ore (iron ore 2), Brasilian iron ore (iron ore 3) and scale (iron ore 4), each with its own chemical composition, i.e. with different lime and silica. Based on the laboratory analysis, are established the values of the following input measures: silica and lime of iron ores, silica and lime of the limestone, as well as the silica and lime from the coke ashes.

Other input measures are prescribed measures, i.e.: basicity index (I), coke ashes' proportion ($Ce\%$), c_0 – ratio between coke and iron ore, r_0 – ratio between the return and iron ore, m_1 – proportion of iron ore 1 against the total iron ore, m_2 – proportion of iron ore 2 against the total iron ore, m_3 – proportion of iron ore 3 against the total iron ore and m_4 – proportion of iron ore 4 against the total iron ore. Because in the sintering charge the total iron ore is considered 100%, it should be fulfilled the condition $m_1+m_2+m_3+m_4 = 1$.

where :

$$m_1 = \frac{M_1}{M}; m_2 = \frac{M_2}{M}; m_3 = \frac{M_3}{M}; m_4 = \frac{M_4}{M} \qquad (46)$$

M_1 – Romanian iron ore flow; M_2 – Krivoi-Rog iron ore flow; M_3 – Brazilian iron ore flow; M_4 – scale flow; M – total iron ore flow.

The input measures s_r (silica in return) and k_r (lime in return) is calculated with a separate subsystem presented in fig. 3.

Because the return is in fact fine-grained agglomerate which is recycled in the process, the silica and lime from the return is equal with the silica and lime of the agglomerate.

The subsystem from fig. 3 makes the calculation of the silica and lime from the return based on the following formulas:

$$S \cdot s_r = M \cdot \sum m_i \cdot s_i + M \cdot c_0 \cdot Ce \cdot s_{Ce} + K \cdot s_k + M \cdot r_0 \cdot s_r \qquad (47)$$

$$k_r = s_r \cdot I \qquad (48)$$

$$s_r = \frac{M \cdot \sum m_i \cdot s_i + M \cdot c_0 \cdot Ce \cdot s_{Ce} + K \cdot s_k}{S - r_0 \cdot M} \qquad (49)$$

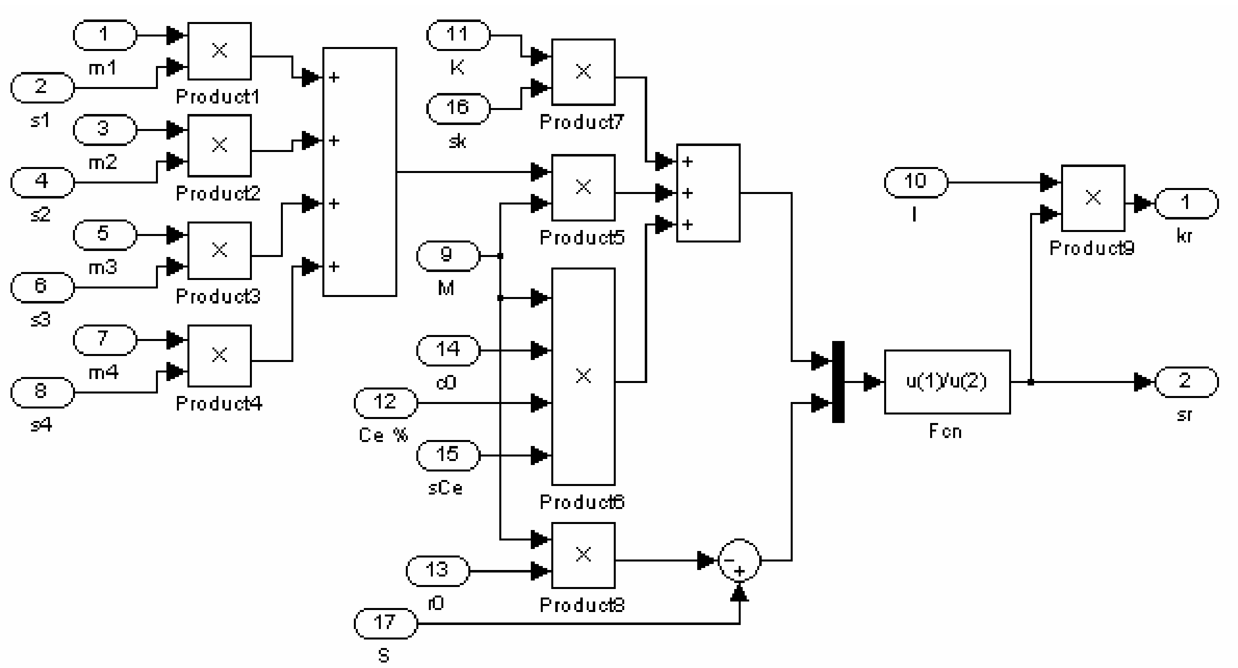

Fig.3. Block diagram for calculation of the lime and silica from the return

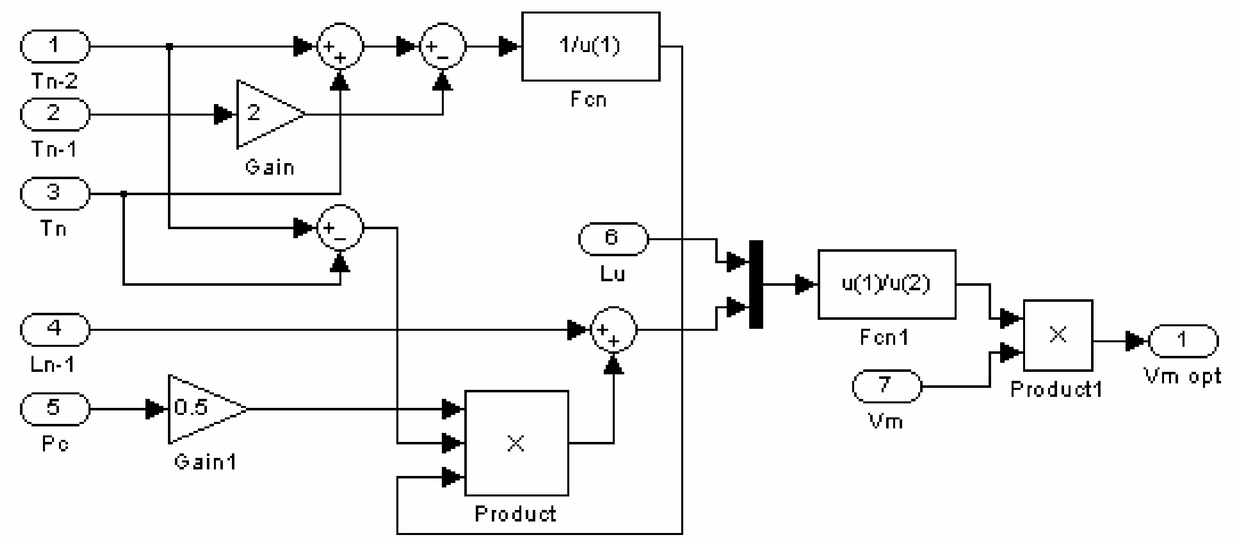

Fig.4. Block diagram for calculation of the sintering line's optimal speed

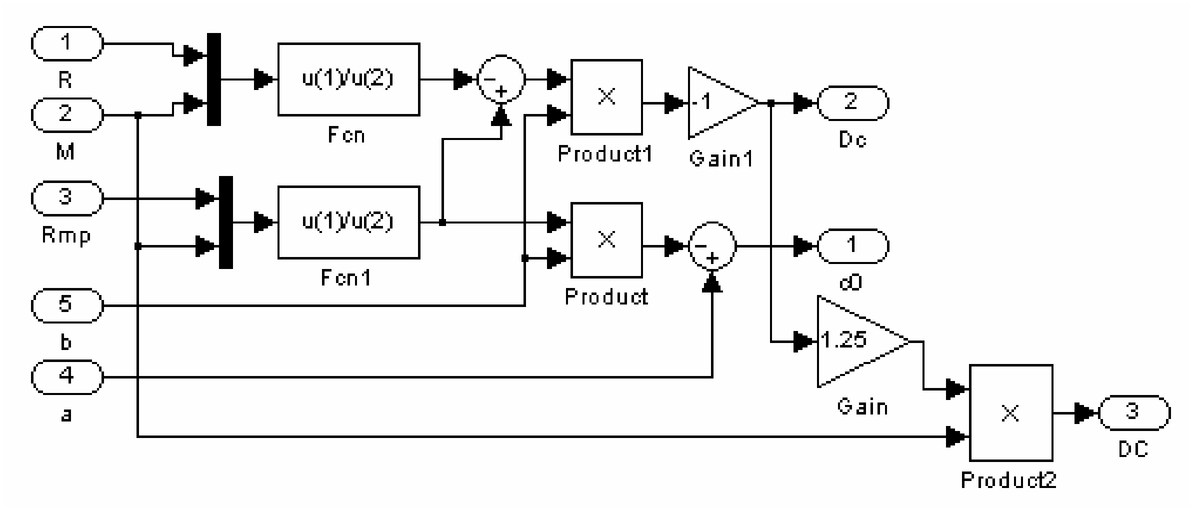

Fig.5. Block diagram for calculation of the coke content's variation from the charge

Using the Simulink program from Matlab environment it was determined the sintering machine's optimal speed variation.

The simulation allowed also to computing the carbon correction from the charge, as well as the charge flow [11]. The calculation subsystem of the sintering machine's optimal speed from fig. 4 has as input measures the following: temperatures in the last three suction chambers (T_n, T_{n-1}, T_{n-2}), the sintering machine's useful length (L_u), the length up to the penultimate suction chamber (L_{n-1}) and the suction chambers' distance (p_C).

The sintering machine's useful length, the length up to the penultimate suction chamber and the suction chambers' distance are considered constant measures (L_u=42 m, L_{n-1}=40 m, p_C=2 m), and the temperatures in the last three suction chambers are considered measures that take different values at certain moments of time.

The sub-system from fig. 5 calculates the carbons correction (coke) that should be made at dosing, in order that the fine-grained return produced in the sintering process (which is scaled) to be equal with the return which is introduced in the sintering charge at dosing. This sub-system is achieved based on the equations (39) and (40).

The input measure S (the sintering charge's flow) is calculated with a separate subsystem presented in fig. 6 based on the following parameters: the sintering band's speed, the sintering layer's height and the sintering band's width. The calculation subsystem of the charge flow presented in fig. 6 is achieved based on the equation (41).

For the temperature values T_{n-2}, T_{n-1} and T_n (the temperatures in the last three suction chambers of the sintering band) expressed at different moments of time, will be obtained the variation curve of the sintering machine's optimal speed. This time-variation curve of the sintering machine's optimal speed can be used successfully for the optimal management of the process from the sintering band.

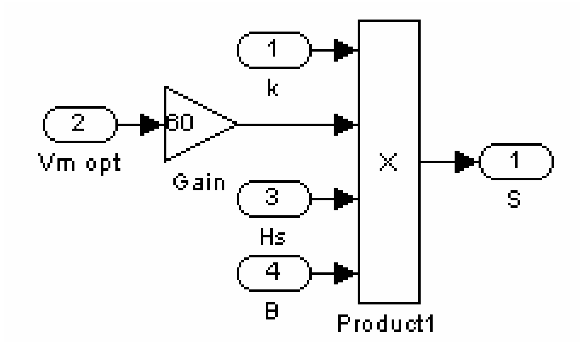

Fig.6. Block diagram for calculation of the charge flow

The temperature values T_{n-2}, T_{n-1} and T_n at different moments of time can be modified, obtaining, depending on these and the other subsystem's inputs, other time-variation curves of the sintering machine's optimal speed.

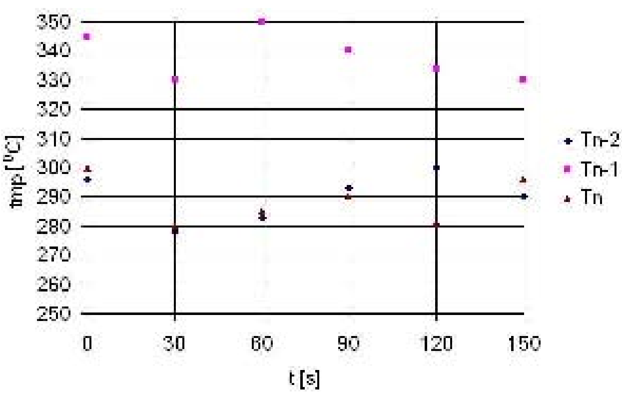

Fig.7. The temperature values for the three suction chambers, in time, for the simulation from fig.8

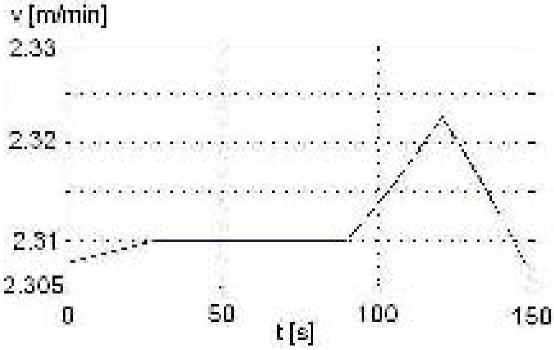

Fig.8. Variation of the sintering machine's optimal speed – case 1

In fig. 8, 10, 12, 14, 16 are presented the variations of the sintering machine's optimal speed for different distributions of the iron ore's temperatures on the sintering band.

The temperature distributions in time, for the last three suction chambers of the sintering machine (T_{n-2}, T_{n-1}, T_n) are given under vectorial form and are presented in fig. 7, 9, 11, 13, 15.

The prescribed speed (for the simulations from fig. 8, 10, 12, 14, 16) for the adjustment system is 2.2 m/s. The temperatures are considered to be measured each with a temperature transducer for each chamber. The simulation time is 150 s, and the temperature readings are made from 30 to 30 s. The measurement of the material's temperature on the sintering band is a difficult operation.

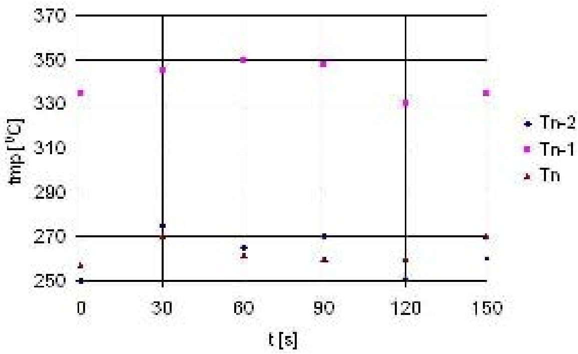

Fig.9. The temperature values for the three suction chambers, in time, for the simulation from fig.10

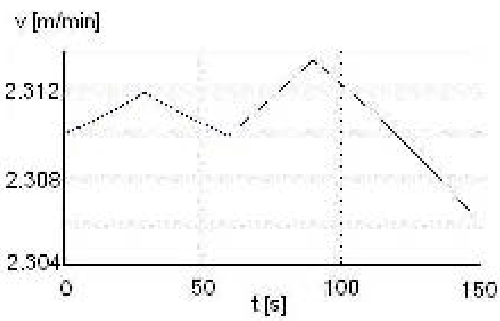

Fig.10. Variation of the sintering machine's optimal speed – case 2

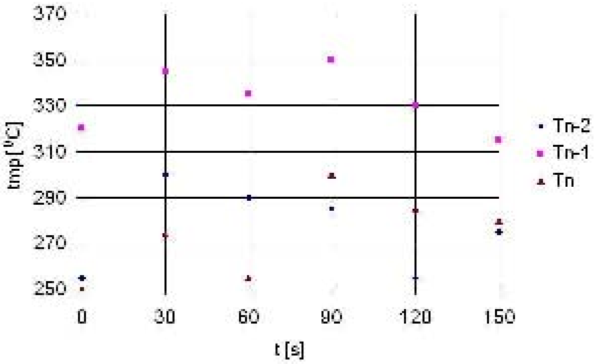

Fig.11. The temperature values for the three suction chambers, in time, for the simulation from fig.12

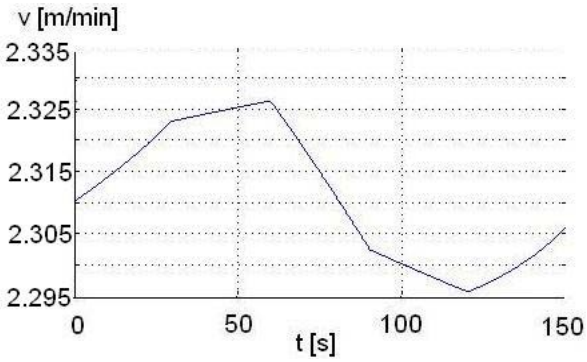

Fig.12. Variation of the sintering machine's optimal speed – case 3

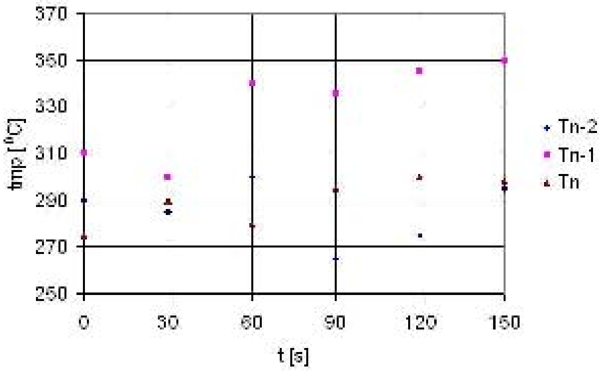

Fig.13. The temperature values for the three suction chambers, in time, for the simulation from fig.14

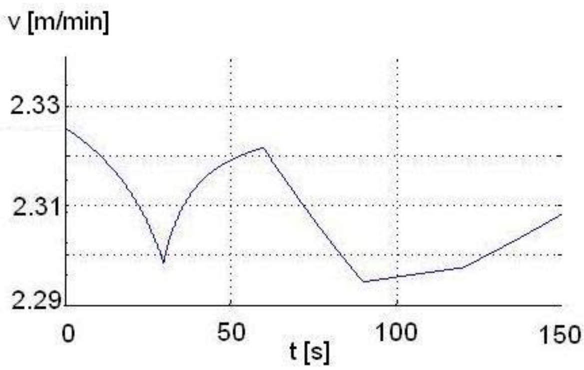

Fig.14. Variation of the sintering machine's optimal speed – case 4

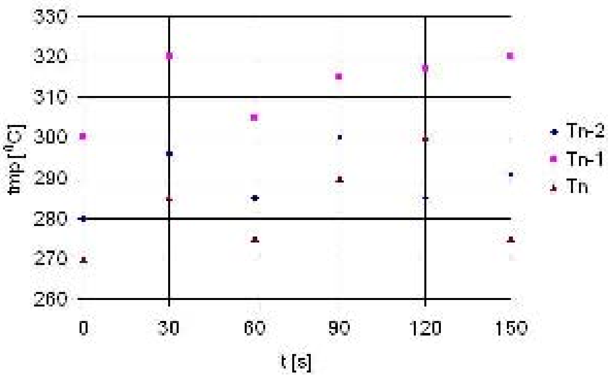

Fig.15. The temperature values for the three suction chambers, in time, for the simulation from fig.16

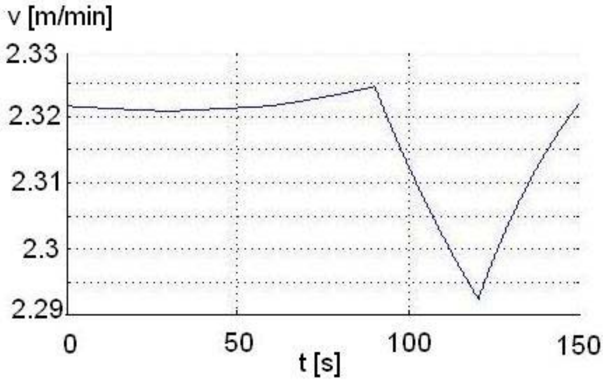

Fig.16. Variation of the sintering machine's optimal speed – case 5

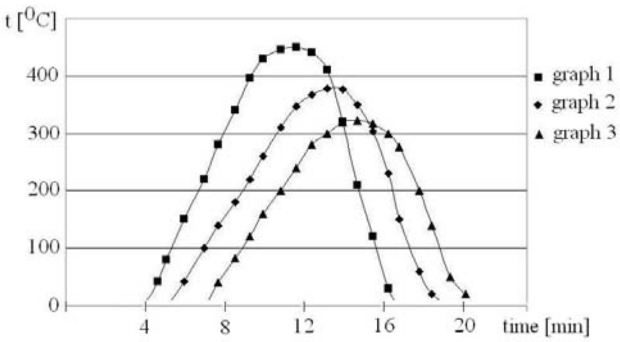

Fig.17. Distribution temperatures, under the layer: graph 1: 20 cm layer; graph 2: 30 cm layer; graph 3: 40 cm layer

From practice, are known the temperature domains for each suction chamber: $T_{n-2} \in [250\text{-}300]$ ^{0}C; $T_{n-1} \in [300\text{-}350]$ ^{0}C; $T_n \in [250\text{-}300]$ ^{0}C.

Depending on the temperatures measured (fig.17) in the suction chambers, the adjustment system imposes a certain modification of the sintering band. For simulations were used the experimental data from fig.17 (graph 3, 40 cm layer).

4 Conclusion

The model achieved in Matlab/Simulink and its simulation allows the determination of the material flows in the charge, either at the variation of their chemical composition, or at variation of the reference values of the parameters S, I, r_0, c_0.

The value of the charge flow S varies as result of the transitory adjusting regime of the sintering machine's speed. The values r_0 and c_0 are established by independent criteria, e.g.: balancing the ore fines circulation, respectively ensuring the optimal compromise, between the agglomerate production on one side and the coke specific consumption on the other side, and between the agglomerate's reducibility and resistance.

Also, the achieved model allows the visualization of the optimal speed in time, which leads to the optimal charge of the sintering machine from the viewpoint of the charge's chemical and mineralogical composition. The obtained results are in accordance with the practical ones, and the model can be implemented to a real installation.

The current technology of cast-iron making imposes more and more rigorous conditions to the quality of the charge that should allow the optimization of the entire process, increasing the productivity and reducing the coke consumption.

As regards the modernization of the iron ores' sintering plants, will be considered the following research directions [12,13,14]:

- Development of an expert system for correcting the sintering belt's speed based on fuzzy logic;
- Development of computerized control systems for adjusting the water quantity in the raw materials and the agglomerate's chemical composition;
- Implementation of a surveillance system in the iron ores' sintering process.

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