HOT METAL DESULFURIZATION PROCESS AS AN OBJECT OF PHYSICAL AND MATHEMATICAL MODELLING

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Abstract

The purpose of the research in hot metal desulfurization process is to identify the main process parameters affecting the final effect of desulfurization. Therefore, the measurable effect of the actions taken should be the improvement of the quality of control. One of the important elements of the project was the physical modelling of the phenomenon of mixing the metal bath during desulfurization. For this purpose, a physical model of an industrial stand was built on a scale of 1: 10, in which measurements were carried out for various variants of the process implementation - parameters such as the flow of gas transporting reactants, the height of the lance position and its internal diameter were regulated. On the basis of the obtained results, the real impact of the method of supplying the desulfurizing agent on the time of complete mixing of the metal bath was assessed. The conducted research became the basis for developing a model of mixing hot metal during desulfurization. Thanks to the availability of both technical and process data of the metallurgical reactor as well as qualitative data of hot metal, it is possible to develop a comprehensive model of desulfurization. The proposed model was based on the tank theory. In the future, this solution will make it possible to simulate the desulfurization process, taking into account all relevant parameters, during the process in a time shorter than the real desulfurization time.

Keywords: Desulfurization, hot metal, extractive metallurgy, mathematical modeling, physical modeling

1. INTRODUCTION

The requirements for the chemical composition of the steels produced are now increasingly difficult to meet. For this reason, proper preparation a metal charge for heat becomes of great importance, and this also applies to the hot metal desulfurization process. Creation a reliable process control system is to guarantee the fulfillment of two basic goals. First goal of the project to improve desulfurization process control as part of the PhD thesis is to obtain the required level of sulfur content in hot metal each time. The second equally important goal for PhD thesis is to optimize process for reduce production costs. Second of the mentioned goals is very important due to scale of steel production with hot metal used. In the available literature, the research carried out so far on the hot metal desulfurization process [1,5] clearly shows that the factors limiting the speed of this process include both static and dynamic parameters. Creating models based on data mining allows to assess the importance of individual process parameters, but does not provide full knowledge about the scale of their impact. That's why creation of fundamental models, which causes many problems during verification, is so important and allows for a full understanding of the process.

According to available literature the most commonly used reagents for desulphurizing hot metal are lime CaO, magnesium Mg, carbide CaC_2 and soda Na_2CO_3. In this case, the described technology includes first two media. Injection method for CaO and Mg into metal bath is using a dip lance and nitrogen as the carrier gas [1-2]. Due to the complex mechanism of the process, it is believed that the factors controlling the rate of

reaction are both thermodynamic and kinetic. The method of writing the kinetics for desulfurization equations is always determined by the original concept adopted mathematical model [3-4]. There are three possibilities in this regard and include: a) Gibbs function minimization model, b) reaction volume model, c) reaction interface model. In the conducted research, a type b model was adopted for implementation [5].

Magnesium as the primary desulfurizing agent has low melting and boiling points of 924 K and 1380 K, respectively, and has a relatively high solubility in liquid iron. Injected to hot metal by submerged lance, it immediately creates a stream of gas bubbles, being partially dissolved in the liquid iron at the same time.

Described mechanism clearly determines reaction sites of magnesium with sulfur dissolved in the bath. These are the surfaces of gas bubbles, hot metal bath volume in the stream zone and the contact zone at the slag-metal interface [6]. Taking into account the presence of injected lime in the system, it can be assumed that the resultant desulfurization rate is described by the **Formula 1:**

$$\frac{d[\%S]}{dt} = \left(\frac{d[\%S]}{dt}\right)_{CaO} + \left(\frac{d[\%S]}{dt}\right)_{Mg} \quad (1)$$

where:

%S - percentage of total sulfur reduction (-)

%S(CaO) - percentage sulfur reduction by adding CaO (-)

%S(Mg) - percentage sulfur reduction by adding Mg (-)

Applying a mathematical model based on tank theory as the basis for the calculations, frees us from need to verify both components of equation's right side separately. However, this requires the construction of a reliable mixing model, which will be basis for thermodynamic calculations using Fact Sage [7]. First stage of the completed research subject is Tank Model (TM) verified for the water model in physical simulation of bath mixing that takes place in tested industrial unit. The result of mathematical model verification for the laboratory stand will be a model's basis for the real object.

Aim of this study is to the phenomenon of mixing the metal bath during the desulfurization process on a physical model and determining the real impact of the method of injection the desulfurizing reagent on the time of complete mixing of the metal bath.

2. EXPERIMENTAL SETUP

Research was carried out on a physical "cold model" designed and built on the model of a real metallurgical unit for desulfurization of hot metal in the scale of 1:10. The test stand consists of: 1) leveling table; 2) water tank; 3) lance; 4) tracer feeding system; 5) transport gas system; 6) rotameter; 7) measuring system: conductivity meter + thermocouple; 8) cylinder with inert gas (nitrogen). Experimental setup is shown in **Figure 1**.

Experimental setup construction allows for adjustment of individual parameters: lance height position from tank's bottom (laboratory rack), transporting gas flow

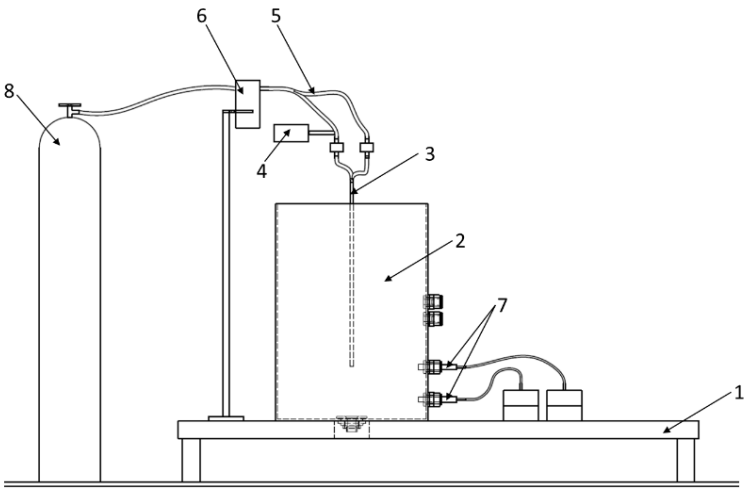

Figure 1 Scheme of experimental setup

(rotameter) and the location of conductivity sensors pairs (water tank has 4 measuring holes corresponding to the position according to TM).

Process flow: inert gas (nitrogen) was injected to distilled water in the water tank by a lance. Constant flow transport gas was fed during mixing simulation. Duration time per one experiment was 160 s and the temperature = constant (~23 °C). A pair of conductivity meters were used for each experiment. Based on the TM theory, location of the conductivity sensors was determined in such a way that there was at least one sensor in each tank, and readings from two different tanks were obtained for one simulation.

3. EXPERIMENT RESULTS

For each realized experiment was created a graph shows change in the conductivity of the bath over time. Due to need to compare simulation results for different configurations of the previously mentioned parameters, their standardization is required. Standardization was carried out according to following formula:

$$C_i = \frac{c_i}{c_r} \tag{2}$$

where:

C_i - standardized tracer concentration (-)

c_i - real tracer concentration (-)

c_r - real tracer concentration in system after reaching equilibrium (-)

An example of a standardized value's graph is shown in **Figure 2**. To calculate complete mixing time for bath after disturbing medium with a tracer, following algorithm was used: for each runs, a time t value was sought for which the standardized value ci was in the range 0.95 ÷ 1.05 (error = +/- 5 %), the simulation time was greater than 15 seconds and for the standardized value c_i, arithmetic mean of difference c_i - c_{i-1} from 10 previous readings didn't change by more than 5%. As the time of complete mixing, a higher value was selected (one graph - two runs for two tanks). Summary of full mixing time (seconds) for min and max medium volume is shown in **Table 1.**

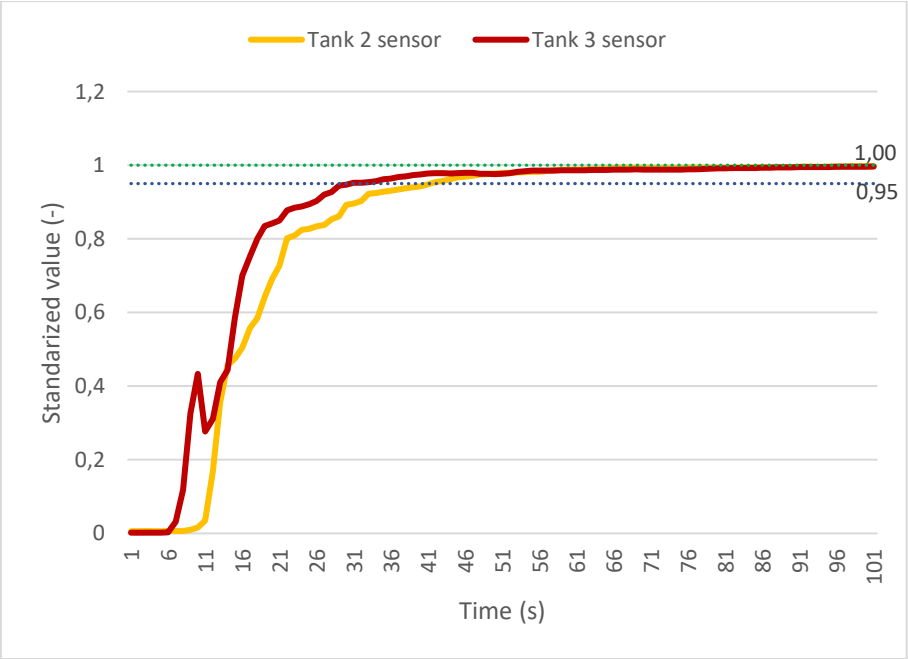

Figure 2 Conductivity curves for changes in the medium for volume 26.5L and N_2 flow: 4L/min

Table 1 Summary of full mixing time in seconds for minimum and maximum medium volume

	Minimum volume 26.5 L			Maximum volume 29.5 L		
Nitrogen flow	**4 L/min**	**7 L/min**	**10 L/min**	**4 L/min**	**7 L/min**	**10 L/min**
Time for sensors: tank 2 & 3	41	28	23	37	30	22
	48	23	10	28	24	22
Time for sensors: tank 1 & 3	53	28	19	38	23	17
	42	26	20	54	47	30

4. TANK MODEL CONCEPT FOR MIXING MODEL

A mathematical approach describing changes in substance concentrations distribution over time can be expressed using Tank Model TM. In this type of mathematical model, a physical model is divided into volume sub-areas, called tanks. Each of these elementary tanks is characterized by a specific type of flow, that affects changes in concentrations over time. For tank which is basic unit of formulated model, is assigned the following properties [8]:

- at any instatnt of time t there is no concentration gradient of reactans within the each tank (ideal mixing)
- streams masses flowing in and out of the bath are defined
- reagents concentrations change in tank occurs in steps, with frequency resulting form the adopted calculation time step

Figure 3 shows tank model structure for hot metal desulfurization simulation in the ladle. Division into individual tanks is: I – 15 %, II – 60 %, III – 25 % total reactor volume. The volumes of individual tanks were determined based on the knowledge provided by research for steel argon treatment. At this point, considerations regarding cold model begin. In the first stage of formulating the mathematical model for the cold physical model, based on the obtained results, the above-proposed % share of individual tanks was arbitrarily adopted [9-10].

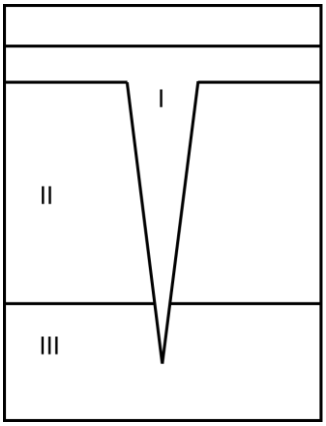

Figure 3 Division of the metal bath into tanks during hot metal desulfurization process

Based on **Figure 3**, the following system the differential equations describing mass exchange in volume of the bath can be formulated:

$$\frac{dm_1}{dt} = \frac{m_2}{V_2} * \dot{V}_{21} * \Delta t + \frac{m_3}{V_3} * \dot{V}_{31} * \Delta t - \frac{m_1}{V_1} * \dot{V}_{12} * \Delta t - \frac{m_1}{V_1} * \dot{V}_{13} * \Delta t \quad (3)$$

$$\frac{dm_2}{dt} = \frac{m_1}{V_1} * \dot{V}_{12} * \Delta t + \frac{m_3}{V_3} * \dot{V}_{32} * \Delta t - \frac{m_2}{2} * \dot{V}_{21} * \Delta t - \frac{m_2}{V_2} * \dot{V}_{23} * \Delta t \quad (4)$$

$$\frac{dm_3}{dt} = \frac{m_1}{V_1} * \dot{V}_{13} * \Delta t + \frac{m_2}{V_2} * \dot{V}_{23} * \Delta t - \frac{m_3}{V_3} * \dot{V}_{31} * \Delta t - \frac{m_3}{V_3} * \dot{V}_{32} * \Delta t \quad (5)$$

where:

m_i - the mass of the component in i-th tank (kg)

V_{ij} - bath volume flow from tank i to j (m^3/s)

V_i - volume of i-th tank (m^3)

Δt - calculation time step (s)

5. EVALUATION OF THE INFLUENCE SELECTED PARAMETERS ON THW BATH MIXING PROCESS

Based on the formulated equations describing the mass flow in the tank (equation 3 ÷ 5) and based on the results of mixing simulations performed on the cold model, the mass exchange streams between individual tanks were determined (**Table 2**).

Table 2 Mixing simulation results based on mass exchange in tanks (L/s) for volume 26.5L, lance position 1, gas flows 4, 7 and 10 L/min

Flow, L/min	Simulation time, s	Experiment time, s	Tank 1→ 2	Tank 1→ 3	Tank 2→ 1	Tank 2→ 3	Tank 3→ 1	Tank 3→ 2
4	41	43	0.35	0.10	0.35	0.15	0.10	0.15
7	28	26	0.45	0.15	0.45	0.20	0.15	0.20
10	23	20	0.55	0.20	0.55	0.25	0.20	0.25

In order to use obtained results for other configurations of parameters such as lance height, gas flow or the volume of the reactor bath, the stream volumes were related to the total reactor volume (e.g. **Table 3**).

On the basis of the conducted research, graphs of the full mixing time for various gas flows (e.g. **Figure 4**) for the experiments on the cold model and the simulation time using the theory of tank models were generated. It can be seen that the complete mixing time of the bath decreases with increase mixing gas flow.

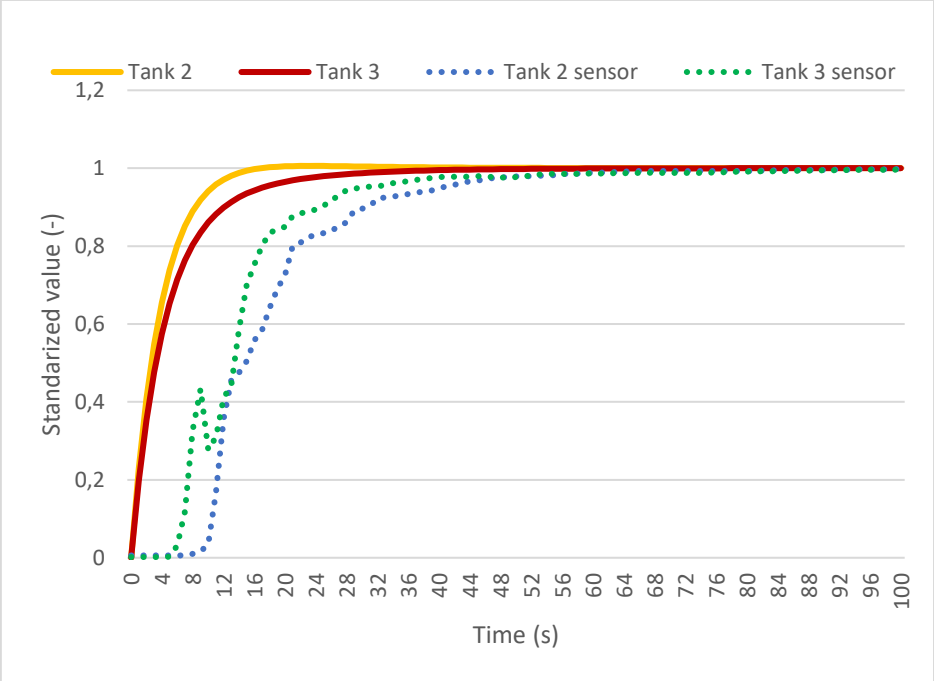

Figure 4 Graph standardized for a volume 26.5L and an N_2 flow 4 L/min

Table 3 Percentage of streams flowing (L/min) between tanks in relation to the total tank volume (L)

	Flow, L/min	Tank 1→2 & 2→1	Tank 1→3 & 3→1	Tank 2→3 & 3→2
Volume: 26.5L Lance position: 1	4	2.6 %	0.8 %	1.1 %
	7	3.4 %	1.1 %	1.5 %
	10	4.2 %	1.5 %	1.9 %
Volume: 26.5L Lance position: 2	4	2.6 %	1.1 %	1.1 %
	7	3.4 %	1.5 %	1.5 %
	10	4.2 %	1.9 %	1.9 %

The modified equation for the flow in tank 1 is represented by **Formula 6**.

$$\frac{dm_1}{dt} = \frac{m_2}{V_2} * \dot{V}_{21} * \Delta t + \frac{m_3}{V_3} * \dot{V}_{31} * \Delta t - \frac{m_1}{V_1} * \dot{V}_{12} * \Delta t - \frac{m_1}{V_1} * \dot{V}_{13} * \Delta t + \boldsymbol{FACT} \quad (6)$$

where:

m_i – the mass of the component in i-th tank (kg)

V_{ij} - bath volume flow from tank i to j (m^3/s)

V_i - volume of i-th tank (m^3)

Δt - calculation time step (s)

FACT - thermodynamic model using the Fact Sage ® software

6. CONCLUSIONS

Experiments carried out on a physical cold model for hot metal desulfurization station made it possible to assess the influence of the main technological parameters on the bath mixing kinetics. On this basis, the mathematical model was verified. Main observations resulting from laboratory tests allow the following conclusions:

- increasing the carrier gas flow rate by 75 % shortens the bath mixing time by 32 %, while increasing it by 250 % shortens it by 44 %
- lowering the lance position by 47 % of the original height reduces the mixing time by an average 20 %
- changing the total reactor volume by 10 % changes time mixing by 26 %

Created mathematical model is the basis for formulating a fundamental model for hot metal desulfurization process. It should be noted that the presented mathematical model, verified on the basis of experiments on the cold model, will be enriched with a thermodynamic model using the Fact Sage ® software. Owning to the fact, it will be possible to simulate changes in the sulfur content in tanks.

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