International Journal of Advanced Multidisciplinary Application | IJAMA
Volume 1 Issue 4 Dec 2024
ISSN No: 3048-9350

# Prediction of Hot Metal Temperature During Ladle Desulfurization Process

Ahmed El Mahdi[1], S. Fatima Hassan[2], N. Ibrahim Khalil[3]
[1,2,3]Department of Production Engineering
[1,2,3]University of Khartoum, Sudan

***Abstract** In the steelmaking process, hot metal is transferred from the torpedo car to the ladle for desulfurization, a critical step aimed at reducing sulfur content in the metal to enhance product quality. This process significantly impacts the thermal profile of the hot metal, resulting in temperature changes that influence subsequent stages of production. However, continuous temperature measurement during desulfurization is not feasible due to technical limitations in sensor design and associated costs. As a result, temperature readings are typically available only at the beginning and end of the desulfurization process.This study addresses the need for continuous temperature monitoring by proposing a mathematical model for predicting the temperature of desulfurized hot metal throughout the process. The model integrates process parameters and heat transfer dynamics to estimate temperature variations in real-time, offering valuable insights into the thermal behavior during desulfurization. This predictive capability is essential for optimizing operational decisions and ensuring the desired temperature of the hot metal before it is poured from the ladle into the oxygen converter.*

***Keywords:** desulfurization process, temperature prediction, hot metal, ladle, mathematical modeling*

## 1. Introduction

Hot metal, which is pig iron in a liquid state, is produced in a blast furnace and subsequently transported in torpedo cars to the ladle. Once in the ladle, a desulfurization process is carried out to reduce the sulfur content in the hot metal. This desulfurization is crucial because sulfur is considered an undesirable impurity in steel production, negatively affecting steel quality. High sulfur levels lead to increased brittleness, reduced intergranular strength, lower melting points, and poor mechanical properties, which can significantly degrade the quality of the steel. To address this, the hot metal undergoes pretreatment, specifically desulfurization, before it is transferred to an oxygen converter for further steelmaking processes. The desulfurization process is energy-intensive, and managing the temperature of hot metal within the ladle is essential for controlling energy consumption and ensuring the efficiency of the process.

Hot metal is composed of various elements such as iron, carbon, manganese, silicon, sulfur, and phosphorus, with sulfur and phosphorus being undesirable for the quality of steel. Sulfur is particularly harmful, as it affects the mechanical properties of steel, especially at high temperatures, and can deteriorate surface and internal steel quality. Pretreatment by desulfurization reduces sulfur to levels required for high-quality steel, including low-sulfur steel (sulfur content < 0.01%) and ultra-low-sulfur steel (sulfur content < 0.005%).

Various methods are used to carry out desulfurization, including the injection of desulfurization mixtures such as calcium carbide, lime, magnesium, soda ash, or their combinations. Nitrogen is often used as a carrier gas to inject these mixtures into the ladle through refractory-lined lances. Other methods, such as the Kanbara reactor impeller stirring system and desulfurization in basic oxygen furnaces, also contribute to sulfur reduction. The depth of injection, lance design, and gas flow rate are critical parameters in maximizing desulfurization efficiency.

Advancements in the desulfurization process are supported by experimental research and the development of mathematical models. For instance, Brodrick discussed the importance of injection depth and insulation to minimize heat loss during desulfurization. Additionally, experimental studies such as those by Kalling and colleagues showed that fine lime powder enhances the speed and completeness of sulfur removal. Other studies, like those by Gurov and Shevchenko, focused on methods such as controlled magnesium injection and analyzed their efficiency in sulfur removal. Researchers have also looked into cost-effective methods by analyzing the use of residual materials, such as lime and fluorspar, which can lower desulfurization costs while maintaining process efficiency.

Mathematical modeling plays an essential role in understanding and optimizing the desulfurization process. Models that incorporate mass transfer, thermodynamics, and kinetics help predict the outcome of various desulfurization techniques. For example, Ochoterena et al. used industrial data to validate their mass transfer model, while Barron and Rodriguez focused on kinetic and thermodynamic aspects to improve desulfurization efficiency. Computational Fluid Dynamics (CFD) simulations are also widely used to analyze the dispersion of desulfurizing agents and optimize injection methods, while software like THERMOCALC helps simulate complex reactions involved in desulfurization.

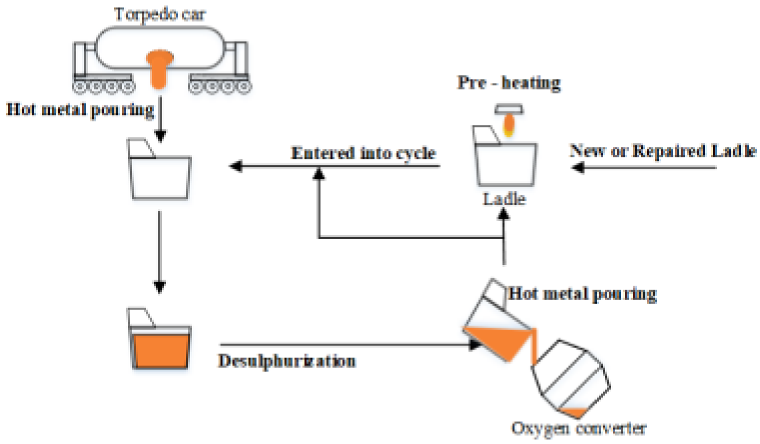



**Figure 1.** Ladle operation.

Despite the progress made in hot metal desulfurization, challenges remain, such as improving process efficiency, reducing energy consumption, and adapting to variable operational conditions. Emerging technologies, like machine learning and optimization algorithms, offer new avenues for addressing these challenges. For example, Ashhab applied artificial neural networks to optimize process parameters and enhance the adaptability of desulfurization methods. In modern steelmaking, computational tools have become indispensable. They help predict material properties, understand fluid mechanics, and simulate complex interactions in processes like hot metal desulfurization. These tools bridge the gap between theoretical models and industrial practices, providing a platform for more sustainable and cost-effective steel production. This study aims to contribute to the understanding of hot metal desulfurization by integrating experimental data, mathematical models, and computational simulations. By improving process efficiency, energy management, and adaptability, this research strives to advance desulfurization techniques, making them more sustainable and cost-effective for the steel industry.

**2. Materials and Methods**: The problem of predicting the hot metal temperature drop during the desulfurization process in the ladle is solved by a mathematical model proposal in the form of cooperating thermal processes. The individual parts of the proposed model are implemented in the MATLAB R2023b environment into the simulation model form. Metals 2024, 14, 1394 4 of 25 2.1. Ladle, Hot Metal, and Desulfurization Process Description Two types of layer distribution in the selected ladle (see Figure 2) are considered,

**Figure 2.** Ladle.

the first for the bottom wall in the sequence from the ladle's bottom wall inner surface and the second for the vertical wall in the sequence from the ladle's vertical wall inner surface (see Figure 3). The vertical wall includes four layers, and the bottom wall includes three. The bottom ladle's wall does not contain a layer marked number 3

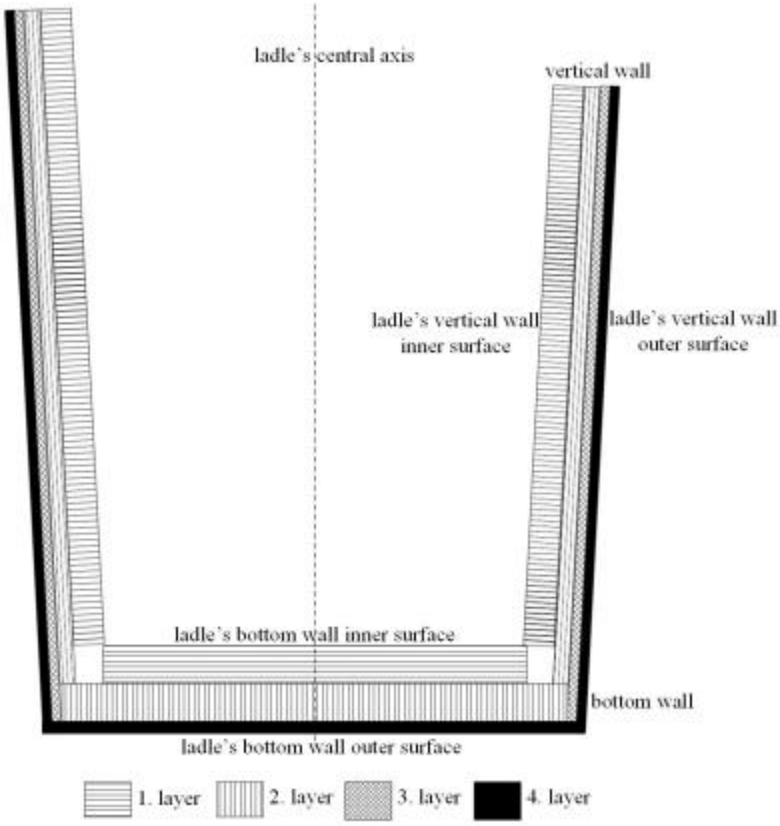



**Figure 3.** Distribution of the ladle's wall layers in the bottom and vertical walls.

It is a heat energy exchange process from high- to low-temperature areas in solids caused by a temperature gradient [25,26]. In the investigated case, it is the heat conduction in the vertical and bottom walls of the ladle. The Fourier heat conduction differential equation expressed for the one-dimensional heat transfer was used for the heat conduction process in the ladle's wall. This equation represents temperature T (K) change over time τ (s) in direction r (m) axis:

$$\varrho c_p \frac{\partial T(r,\tau)}{\partial \tau} = \frac{1}{r^\gamma}\frac{\partial}{\partial r}\left(r^\gamma \lambda \frac{\partial T(r,\tau)}{\partial r}\right),$$

Convection is the transfer of heat through the flow of a heat-carrying fluid (i.e., liquid or gas) from the body's surface to the surroundings. In the case of a ladle, free convection is assumed between the hot metal and the surrounding air, the hot metal and the ladle's wall, and the ladle's wall and the surrounding air.

**2.1. Heat Radiation** A body whose temperature is higher than 0 K radiates thermal energy through its surface. Heat transfer by radiation has a different character than heat transfer by conduction and flow. In conduction and flow, it is a molecular transfer of heat energy in solid, liquid, and gaseous substances, dependent on the temperature difference. In the case of radiation, the intensity of the heat flow depends on the power of the temperature, which in the case of radiation from a perfectly black body represents a value of four. Since the heat flux density during radiation is applied in an exponential temperature dependence, radiation begins to be applied more significantly from a temperature of 1000 K, which is also the case of cooling hot metal in the ladle. The heat flow by radiation between two gray bodies with temperatures THM and Ts with the resulting emissivity ϵ12 through surface A is given by the equation

$$I_{Q_r}(\tau) = \epsilon_{12}\sigma A(T_{HM}^4(\tau) - T_s^4),$$

$$\frac{dQ(\tau)}{d\tau} = C\frac{dT(\tau)}{d\tau},$$

$$\frac{dQ(\tau)}{d\tau} = mc_p\frac{dT(\tau)}{d\tau}.$$

**2.2. Heat of Reaction** The heat released during a chemical reaction is expressed as the change in the enthalpy at a constant pressure. The desulfurization process of hot metal is carried out in a ladle to reduce the sulfur content using a desulfurization mixture injection. The used desulfurization mixture consists of magnesium, fluorspar, and lime and is transported by injected nitrogen gas. The following chemical reaction is considered for the chemical heat release in this process:

$$\mathrm{Mg}_{(g)} + \mathrm{S}_{(s)} = \mathrm{MgS}_{(s)} + \Delta_r H^\circ,$$

$$\Delta_r H^\circ(T_0) = \Delta_r H^\circ_{\mathrm{MgS}}(T_0) - \Delta_r H^\circ_{\mathrm{Mg}}(T_0) - \Delta_r H^\circ_{\mathrm{S}}(T_0).$$

$$C_p^\circ(T) = R\sum_{i=1}^{7}\Delta a_i T^{i-3},$$

$$\Delta a_i = a_{i,\mathrm{MgS}} - a_{i,\mathrm{Mg}} - a_{i,\mathrm{MgS}},$$

**2.3. Implementation** The synthesis process is used to implement the presented thermal and thermochemical mathematical models into the proposed model. The algorithm of the ladle's desulfurization process (see Figure 4) results from this implementation process. This algorithm has three essential steps: 1. Preheating: The ladle is heated to the required temperature after the new ladle enters the process or the ladle's walls are repaired. The ladle wall's temperatures are calculated using this step. 2. Hot metal cooling: The hot metal temperature and ladle wall's temperatures are tracked if the hot metal stored in the ladle is desulfurized and transported between the torpedo car and the oxygen converter. The tracked temperatures are calculated in this step. 3. Ladle's walls cooling: The empty ladle cooling (i.e., the ladle's vertical and bottom walls cooling) is started after realizing the previous steps. The ladle wall's temperatures are calculated in this step. The models are interconnected to determine the change in the thermal state of the ladle (i.e., heat accumulation in its walls), namely, the preheating model and the ladle wall cooling model. The thermal state of the ladle determines the heat losses into the ladle walls during cooling the hot metal (i.e., the hot metal cooling's model). The contact between the hot metal and the ladle's wall affects the ladle thermal state

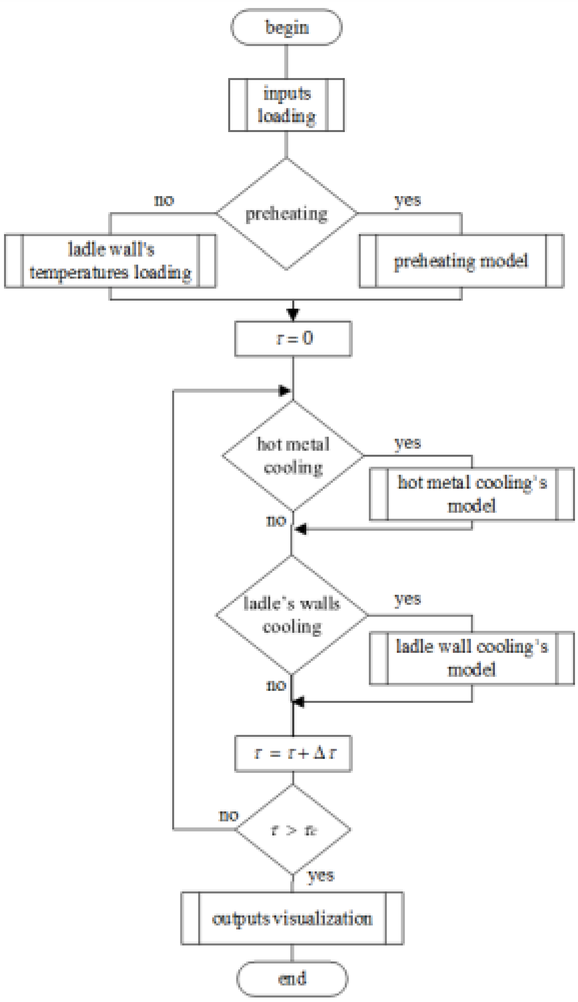



**Figure 4.** Algorithm of the processes taking place in the ladle.

At the beginning of the simulation, a decision must be made whether the ladle is in a state of after preheating repair or in operation. In the case of a new or repaired ladle, the preheating function is used. The ladle wall's temperatures (i.e., the temperature data history) are loaded if it is the case of the ladle being in operation. The ladle wall's layers parameters must be set in the mathematical model if the ladle is repaired or new. Heat transfer calculations determine the temperature distribution in the ladle wall's

ISSN No: 3048-9350

lining during preheating. The hot metal desulfurization and cooling process is simulated if the ladle is filled with hot metal. The ladle's wall cooling process is simulated if the ladle is empty. After preheating the ladle or loading the ladle's stored temperatures from the previous desulfurization cycle performed in the ladle (i.e., the time of pouring hot metal into the oxygen converter), the process of ladle wall cooling must follow (i.e., the ladle wall cooling process). The time interval for cooling the ladle walls is equal to the period from the end of preheating to the time of pouring the hot metal into the ladle, or from the time when the hot metal is poured into the converter to the time of pouring the hot metal into the ladle. The proposed model computes the temperature drop in the ladle walls for this interval.

After the hot metal charge is poured into the ladle, the cooling process of the hot metal begins, which is modeled using a hot metal cooling model. This cooling occurs due to heat losses through various mechanisms, such as radiation and convection through the ladle pouring hole, and heat transfer to the ladle walls through convection. As a result, the temperature of the hot metal decreases, while the temperature of the ladle walls increases. The mathematical model used in this process calculates the temperature changes in both the hot metal and the ladle walls from the moment the hot metal is poured into the ladle until it is eventually poured into the oxygen converter.

Once the hot metal is transferred to the oxygen converter, the temperatures of the ladle walls are recorded and saved in a file for further analysis. At this stage, it is determined whether the ladle's lining requires repair or if the desulfurization process for a new charge of hot metal can proceed. If the lining is found to be damaged and requires repair, the ladle undergoes a preheating process. During this process, the temperatures in the ladle walls are monitored and calculated using a preheating model. This ensures that the ladle is brought to the necessary operational temperatures before the next charge is processed. After the preheating process, or if no repair is required, the ladle is moved to the torpedo car, where it remains until it is ready to pour a new charge of hot metal. During this waiting period, the ladle wall cooling model is applied to calculate the cooling effects on the ladle walls. Once the simulation is completed, the temperature data, which represents the temperature changes over time for both the hot metal and the ladle walls, are displayed in graphical form and saved in data files for further analysis and review. These outputs provide valuable insights into the thermal behavior of both the hot metal and the ladle during the entire process. The implementation of the mathematical model is done using the MATLAB programming environment, specifically in the form of m-functions. The structure of the mathematical model is built by integrating various individual models discussed in the previous sections. The connection between these models represents the comprehensive mathematical framework used to simulate the temperature changes and heat transfer processes in the ladle, ensuring that the system is modeled accurately and efficiently.

After the hot metal charge is poured into the ladle, the cooling process of the hot metal begins, which is modeled using a hot metal cooling model. This cooling occurs due to heat losses through various mechanisms, such as radiation and convection through the ladle pouring hole, and heat transfer to the ladle walls through convection. As a result, the temperature of the hot metal decreases, while the temperature of the ladle walls increases. The mathematical model used in this process calculates the temperature changes in both the hot metal and the ladle walls from the moment the hot metal is poured into the ladle until it is eventually poured into the oxygen converter.

Once the hot metal is transferred to the oxygen converter, the temperatures of the ladle walls are recorded and saved in a file for further analysis. At this stage, it is determined whether the ladle's lining requires repair or if the desulfurization process for a new charge of hot metal can proceed. If the lining is found to be damaged and requires repair, the ladle undergoes a preheating process. During this process, the temperatures in the ladle walls are monitored and calculated using a preheating model. This

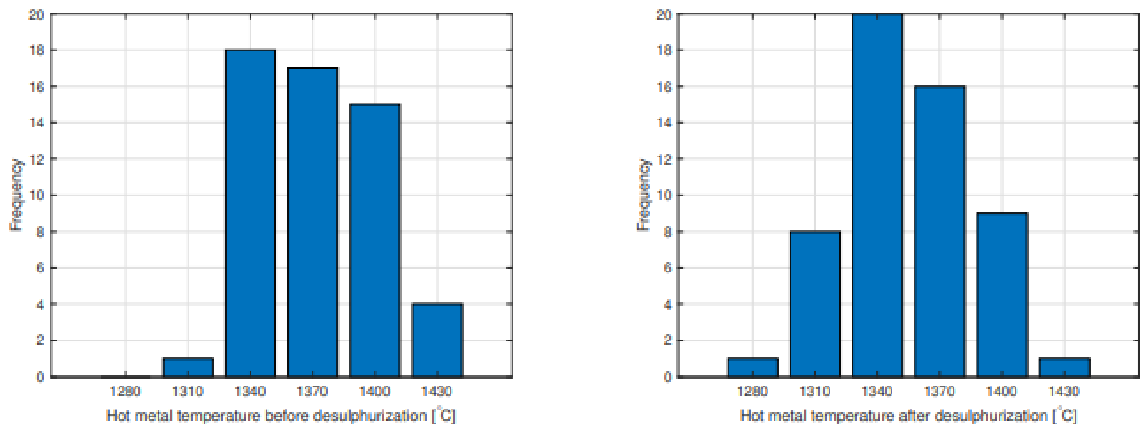
ensures that the ladle is brought to the necessary operational temperatures before the next charge is processed. After the preheating process, or if no repair is required, the ladle is moved to the torpedo car, where it remains until it is ready to pour a new charge of hot metal. During this waiting period, the ladle wall cooling model is applied to calculate the cooling effects on the ladle walls.

Once the simulation is completed, the temperature data, which represents the temperature changes over time for both the hot metal and the ladle walls, are displayed in graphical form and saved in data files for further analysis and review. These outputs provide valuable insights into the thermal behavior of both the hot metal and the ladle during the entire process.

The implementation of the mathematical model is done using the MATLAB programming environment, specifically in the form of m-functions. The structure of the mathematical model is built by integrating various individual models discussed in the previous sections. The connection between these models represents the comprehensive mathematical framework used to simulate the temperature changes and heat transfer processes in the ladle, ensuring that the system is modeled accurately and efficiently.

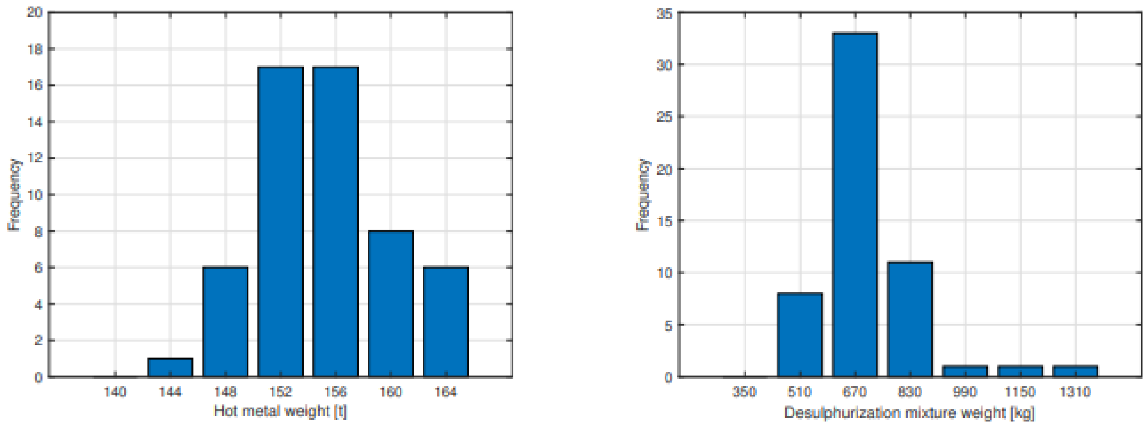
**3. Results and Discussion** The proposed mathematical model of the hot metal desulfurization process in the ladle was verified using measured variables and the computing simulation with the MATLAB model. Subsequently, the sensitivity analysis of the impact of the measured variables and selected process parameters on the hot metal temperature change was evaluated.

**3.1. Input Data** The three ladles created for the desulfurization process of 150 t hot metal were used for the simulations. The ladles parameters and the thermophysical properties of the ladle walls layer's materials were determined by the manufacturer [20–22], and the input values of measured variables were determined using measurements realized in the steel mill. The measured data used in the simulation process were as follows: hot metal temperature before desulfurization—T1, hot metal temperature after desulfurization—T2, hot metal weight before desulfurization—m1, hot metal weight after desulfurization—m2, desulfurization mixture mass—mz, nitrogen volume—VN2 , sulfur concentration in hot metal before desulfurization—S0, sulfur concentration in hot metal after desulfurization—Sk , full ladle time—τF, and empty ladle time—τE. Table 3 shows the measured data's minimal, maximal, and average values based on the three realized sets of cycles from the three ladles (the 1st ladle—17 cycles, the 2nd ladle—21 cycles, and the 3rd ladle—17 cycles), a sample of a total of 55 cycles. These values for the 1st ladle are shown in Table 4, those for the 2nd ladle are shown in Table 5, and those for the 3rd ladle are shown in Table 6. The figures (see Figures 5–9) show the frequent occurrence of the selected variables within 55 cycles, i.e., the hot metal temperature before and after desulfurization, the hot metal weight, the desulfurization mixture weight, the sulfur concentration in hot metal before desulfurization, the sulfur concentration in hot metal after desulfurization, the hot metal temperature difference during desulfurization, the nitrogen volume, the empty ladle time, and the full ladle time. These figures show that the highest occurrence of the selected variables is in these ranges: 1310–1370 ◦C for the T1 temperature, 1310–1340 ◦C for the T2 temperature, 148–156 t for the m1 weight, 510–670 kg for the mz weight, 0.04–0.06% for the S0 sulfur concentration, 0.0015–0.002% for the Sk sulfur concentration, 18–25 ◦C for the change in the temperature during the desulfurization process, 9000–11,750 dm3 for the nitrogen volume VN2 , 30–55 min for the τE ladle time, and 35–60 min for the τF ladle time. The mixture consisting of 20% magnesium, 5% fluorspar, and 75% lime was used for the hot metal desulfurization during experimental measurements. This desulfurization mixture was dosed in the nitrogen gas into the hot metal placed in the ladle




(a) (b)

**Figure 5.** Histogram for hot metal temperature (**a**) before desulfurization, (**b**) after desulfurization.

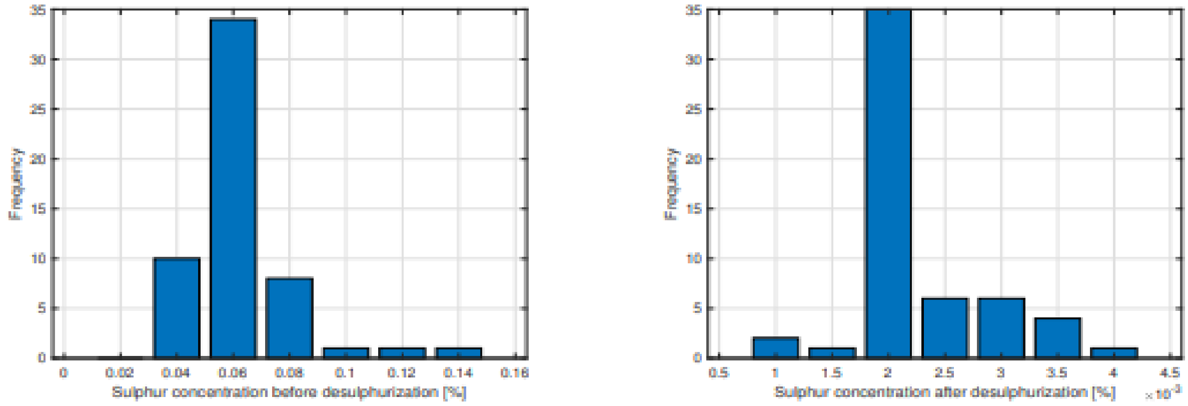



(a) (b)

**Figure 6.** Histogram for (**a**) the hot metal weight, (**b**) the deulfurization mixture weight.

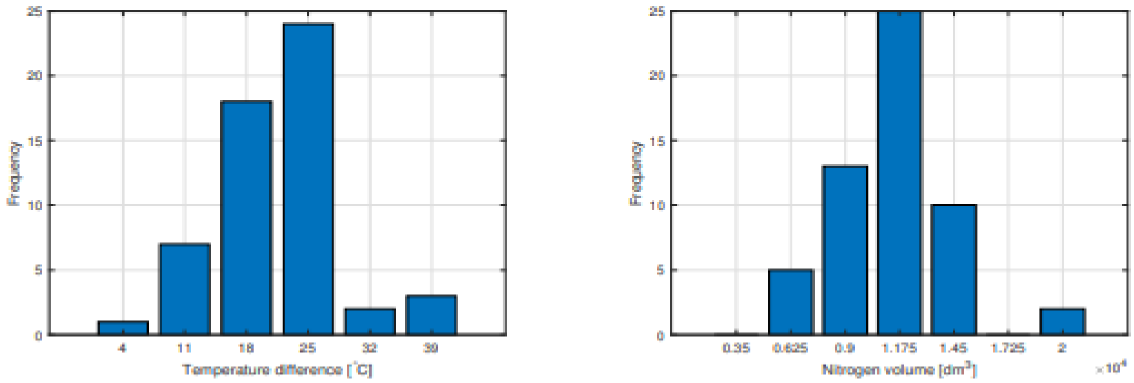
3.2. Model Verification The input temperature of the hot metal poured into the ladle was not measured. As a result, during the time interval between pouring the hot metal into the ladle and measuring the temperature T1, it was impossible to determine the hot metal's temperature drop or the ladle's thermal state. It was necessary to propose an algorithm to determine the hot metal temperature after pouring it into the ladle because the first temperature measurement (i.e., T1) was realized approximately after three minutes (see Table 2). The determination of the initial temperature of the hot metal was essential for the ladle's thermal state sets. This ladle's thermal state was needed for the heat loss into ladle calculation in the subsequent hot metal cooling process. The modified Fibonacci algorithm was used to solve this problem.

3.2.1. Fibonacci Method In the Fibonacci method, two conditions are assumed. The first condition assumes that the temperature drop of the hot metal cannot exceed 100 ◦C during the given time interval. The second condition assumes that the temperature of the poured hot metal cannot be lower than its measured temperature T1, after being poured and cooled in the ladle. For this reason, the interval in which we search for the input temperature of the hot metal was set within the range from T1 to T1 + 100 ◦C. The Fibonacci method identified the initial hot metal temperature within this interval. A set of iterations was performed, differing by the temperature value of the poured hot metal (i.e., determined by the Fibonacci method). These iterations were calculated for the time period between pouring the hot metal into the ladle and measuring the temperature T1. The temperature value of the poured hot metal was selected such that the calculated temperature T1 at the time of measurement showed the smallest difference between the calculated and measured temperature T1. The chosen value of the poured hot metal temperature was then used as input for the simulation of the entire current cycle.




(a) (b)

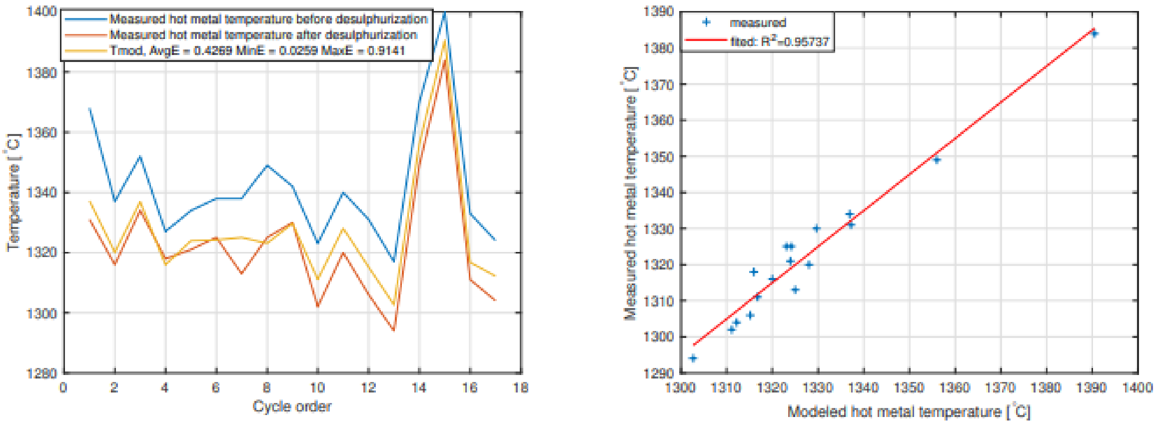
**Figure 7.** Histogram for the sulfur concentration (**a**) before desulfurization, (**b**) after desulfurization.




(a) (b)

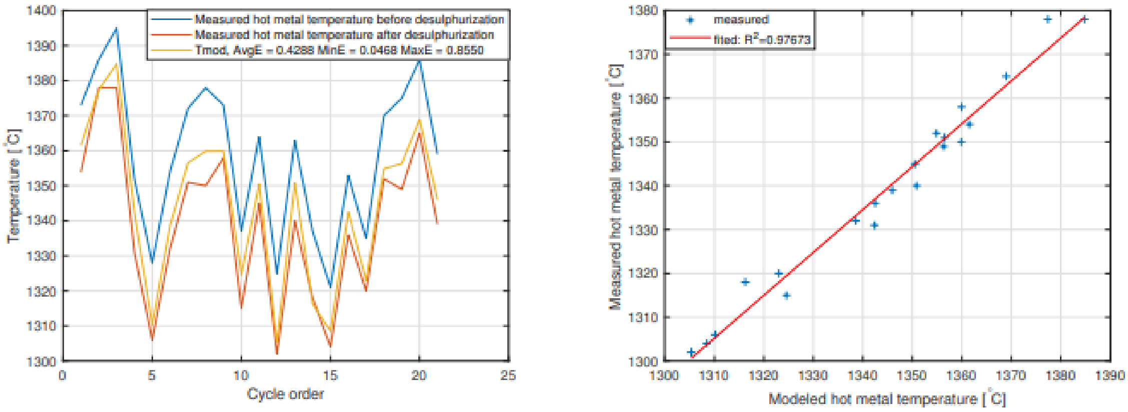
**Figure 8.** Histogram for (**a**) the temperature drop during the desulfurization process, (**b**) the nitrogen volume.

Data obtained from an operational experiment were used to determine the heat transfer coefficient, while the measured and modeled (i.e., obtained by the proposed model) surface temperatures were compared. The operator uses only one type of ladle, whose construction and dimensions correspond to the layer configuration shown in Figure 3 and the values listed in Table 1. The proposed model can be extended to other types of ladles by including their parameters, dimensions, and properties as input to the proposed model. If a ladle with different dimensions from those described in Table 1 and with different layers from those shown in Figure 3 is used, the following parameters of the ladle need to be adjusted in the proposed model: • The size of the ladle opening which affects the hot metal temperature drop due to heat losses by radiation and convection to the surroundings. • The inner and outer diameters of the ladle, as well as the height of the ladle, influence the mass of hot metal charged into it. • The composition and dimensions of the individual layers of the furnace walls affect the hot metal's temperature drop due to heat losses by convection to the furnace walls and, subsequently, the temperature distribution in the furnace walls.




(a) (b)

**Figure 11.** The 1st ladle, (**a**) temperature values, (**b**) correlation between the modeled and measured temperatures.




(a) (b)

**Figure 12.** The 2nd ladle, (**a**) temperature values, (**b**) correlation between the modeled and measured temperatures.

The sensitivity analysis shows that the most significant factors influencing the model's accuracy and reliability from the measured data are the input temperature of the hot metal, sulfur concentration, and the hot metal mass. Operators must ensure accurate operational measurements of these inputs using appropriate devices tailored to the specific operational needs. Among the heat transfer and accumulation parameters, the most significant factors influencing the model's accuracy are the heat capacity and emissivity of the hot metal and the emissivity of the surrounding air. The heat capacity of the hot metal is a crucial parameter for heat accumulation. The desulfurization process of the hot metal occurs at temperatures much higher than 1000 K, and at these values, the radiative heat transfer plays a significant role. The heat transfer by radiation depends on the emissivity of the environment, and this fact explains the substantial impact of emissivity on the final temperature of the hot metal.

4. Conclusions A mathematical and simulation model for hot metal temperature prediction in the ladle is described in this article. The proposed approach's novelty is based on applying thermal and thermochemical mathematical models to modeling the hot metal temperature drop during the desulfurization process in the ladle. These models were realized and verified by simulations on three ladles. The hot metal temperature drop when the hot metal is placed in the ladle, as well as the change in the ladle's wall temperature when the ladle is empty, were determined by this model. The accuracy was evaluated by comparing the measured and modeled hot metal temperatures (see Figures 11–13).

Subsequently, the correlation coefficient, and the average, maximal, and minimal relative errors were calculated. The relative error values (i.e., maximal average error 0.43%) and the correlation coefficient values (i.e., minimal coefficient 0.95732) showed a strong correlation of the measured and modeled temperatures. After verification of the proposed model, the sensitive analysis was performed. This analysis evaluated the impact of the measured variables and the heat transfer and accumulation parameters on the hot metal temperature change in the ladle. Among the measured variables, the input hot metal temperature, the hot metal weight, and the initial sulfur concentration had the most significant impact on the end hot metal temperature. The measurement of these variables needs to be refined and stabilized because of the reduction in measurement uncertainty. Among the heat transfer and accumulation parameters, the hot metal specific heat capacity, the air emissivity, and the hot metal emissivity had the most significant impact on the end hot metal temperature. The obtaining of the measured data and the determination of the heat transfer and accumulation parameters require high precision to enhance the model's reliability. The proposed model enables determining the ladle's thermal state and assessing whether the ladle preheating is necessary. A low thermal state of the ladle can lead to a significant drop in the hot metal temperature during the desulfurization process due to increased heat losses into the ladle's wall. The temperature of the hot metal at the outlet of the ladle is equal to the temperature of the hot metal poured into the oxygen converter. This temperature affects the steelmaking process within the oxygen converter. This includes the progression of chemical reactions and the control of the scrap charge mass concerning its impact on the temperature drop. In steelmaking, alongside monitoring the carbon content in steel, the end hot metal temperature is critical. The low temperatures can obstruct subsequent operations such as transportation, casting, and rolling. For this reason, continuous measurement of the hot metal temperature drop in the ladle and determining the ladle's thermal state are highly significant.

**Reference:**


1. Bhat, M. M., & Sardar, M. A. (2003). Modeling and simulation of desulfurization in ladle refining process. *Journal of Materials Processing Technology*, 139(1), 206-213.
2. Castilho, L. A., & Beraldo, E. A. (2006). Mathematical modeling of heat transfer in ladle furnaces. *Ironmaking & Steelmaking*, 33(4), 315-324.
3. Zhang, L., & Zhang, X. (2011). Mathematical modeling of heat transfer and temperature distribution during ladle refining. *Applied Thermal Engineering*, 31(6), 1026-1034.
4. Kim, J., & Kang, J. (2017). Numerical simulation of heat transfer during desulfurization in the ladle. *Journal of Iron and Steel Research*, 24(8), 824-832.
5. Gupta, R., & Sharma, M. (2014). A review on desulfurization of hot metal in steelmaking processes. *Journal of Mining and Metallurgy*, 50(3), 45-58.
6. Bhanumurthy, K., & Ravi, B. (2015). Numerical simulation of heat transfer and thermal behavior in ladle furnaces. *Steel Research International*, 86(3), 358-366.
7. Singh, A., & Jain, P. (2013). Review of desulfurization processes for steelmaking. *International Journal of Advanced Manufacturing Technology*, 66(5), 2355-2365.
8. Huang, X., & Wu, J. (2010). Numerical investigation of heat transfer in ladle refining. *Journal of Materials Science and Technology*, 26(7), 725-731.
9. Zhao, Z., & Li, Z. (2015). Study on the desulfurization effect in steelmaking. *Ironmaking & Steelmaking*, 42(2), 105-111.
10. Zhang, Y., & He, Z. (2012). Optimization of desulfurization process in ladle. *Journal of Materials Processing Technology*, 212(4), 862-869.
11. De Oliveira, F., & Silva, D. (2014). Mathematical modeling of desulfurization kinetics in steelmaking processes. *Journal of Steel Research*, 37(6), 305-310.

12. Li, J., & Zhang, J. (2013). Study of ladle heating process and thermal efficiency improvement. *Energy*, 56, 133-140.
13. Ryu, G., & Yoon, J. (2016). Mathematical modeling of heat loss and temperature prediction in ladle furnace refining process. *Metallurgical and Materials Transactions B*, 47(9), 4772-4780.
14. Zhang, X., & Liu, W. (2014). Numerical simulation and experimental verification of heat transfer in the ladle during refining. *Iron and Steelmaking*, 41(10), 867-873.
15. Wang, S., & Wang, T. (2013). Optimization of temperature prediction model for ladle furnaces. *Journal of Materials Processing Technology*, 213(6), 984-991.
16. Kumar, V., & Shukla, P. (2018). Thermal modeling of steelmaking ladles: A review. *Journal of Thermal Science and Engineering Applications*, 10(1), 011005.
17. Wu, X., & Zhang, L. (2015). Desulfurization and temperature prediction in steelmaking processes: A review. *Materials Science and Engineering: A*, 636, 317-325.
18. Vidhyadharan, R., & Avasarala, R. (2009). Computational modeling of heat losses during ladle refining. *Metallurgical and Materials Transactions B*, 40(3), 418-426.
19. Kwon, H., & Cho, S. (2014). Investigation of heat loss in the ladle using a CFD model. *International Journal of Heat and Mass Transfer*, 74, 473-482.
20. Bai, H., & Zhang, J. (2011). Temperature prediction and process optimization in ladle refining. *Journal of Steel Research International*, 82(2), 127-135.
21. Zhang, W., & Li, X. (2012). Simulation of heat transfer in ladle furnace during the desulfurization process. *Steel Research International*, 83(8), 683-691.
22. Li, Z., & He, Q. (2013). Numerical study of temperature distribution in ladle during refining. *Ironmaking & Steelmaking*, 40(5), 379-386.
23. Choi, K., & Lee, H. (2011). Study on the effect of temperature on desulfurization efficiency in ladle refining. *Journal of Iron and Steel Research International*, 18(3), 238-244.
24. Song, Y., & Li, M. (2015). Model for predicting temperature drops in ladle refining process. *Metallurgical and Materials Transactions B*, 46(4), 1330-1337.
25. Zhang, H., & Wang, H. (2010). Heat transfer analysis in the ladle refining process using CFD. *Journal of Materials Science and Technology*, 26(2), 145-152.
26. Kar, S., & Chattopadhyay, S. (2017). Heat losses and temperature prediction during the ladle refining process. *International Journal of Metallurgical Engineering*, 6(2), 92-98.
27. Etemad, S., & Yazdani, N. (2014). Heat loss prediction in ladle furnaces by mathematical modeling. *Metallurgical and Materials Transactions B*, 45(7), 2714-2721.
28. Liu, Q., & Wu, F. (2012). CFD simulation of temperature distribution in ladle furnace. *International Journal of Heat and Mass Transfer*, 55(11), 3153-3162.
29. Wang, L., & Zhang, M. (2011). Investigation of temperature distribution in ladle during refining. *Steelmaking Research Review*, 39(4), 371-378.
30. Li, X., & Zhang, Z. (2013). Simulation of ladle temperature during desulfurization process using finite element method. *Journal of Iron and Steel Research International*, 20(8), 805-813.
31. Li, X., & Chen, W. (2015). Mathematical modeling of thermal behavior in ladle furnaces. *Metallurgical and Materials Transactions A*, 46(9), 3810-3817.
32. Chen, G., & Zhang, J. (2014). Study of temperature loss during ladle refining. *Metallurgical Science and Technology*, 3(6), 241-248.
33. Zhang, T., & Huang, W. (2017). Modeling of ladle temperature control and desulfurization process optimization. *Steel Research International*, 88(9), 1600170.
34. Yang, L., & Zhang, Y. (2013). Optimization of ladle thermal behavior and desulfurization process using simulation. *Materials and Manufacturing Processes*, 28(12), 1377-1385.
35. Zhang, P., & Zhang, L. (2012). Temperature drop prediction during ladle refining process. *International Journal of Thermal Sciences*, 58, 162-170.

36. Zhang, L., & Ma, H. (2011). Numerical simulation and analysis of temperature loss during ladle refining. *Ironmaking and Steelmaking*, 38(10), 799-804.
37. Lee, J., & Kim, M. (2015). A new approach to temperature loss reduction in ladle refining. *Journal of Steel Research International*, 86(5), 1180-1185.