Journal of Green
Chemical and Environmental Engineering

e-ISSN 3090-2568
p-ISSN 3109-2233
Research Paper

Technical Assessment and Optimization of Off-Gas Cooling in Nickel Matte Pyrometallurgy Based on Carbon Variation

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Received 5 Feb 2026
Revised 15 March 2026
Accepted 27 March 2026

Citation: Badaruddin, S., Alif Nur Laili Rachmah, Taipabu, M. I., Farida Diyah Hapsari, & Esther Muatiara Santallum Ekklesia Tibalia. (2026). Technical Assessment and Optimization of Off-Gas Cooling in Nickel Matte Pyrometallurgy Based on Carbon Variation. *Journal of Green Chemical and Environmental Engineering*, *2*(1), 1-12.

doi: 10.63288/jgcee.v2i1.21

Abstract: Exhaust gas emission management is a critical aspect of pyrometallurgical nickel smelting because it directly affects energy efficiency, operational safety, and overall process sustainability. This study investigates the influence of calcine carbon content on exhaust gas formation and determines the required cooling air volume in an industrial electric furnace operating at approximately 150 tons per hour. The research is based on deterministic mass and energy balance modelling developed from actual operational data obtained from a nickel smelting facility. The analysis quantifies the relationship between carbon oxidation reactions and off-gas generation during the smelting process. Results reveal a strong linear correlation between increasing calcine carbon content and exhaust gas volume. At an average carbon content of 1.96 %, the furnace produces 47,241 Nm^3/h of exhaust gas. Under these operating conditions, a cooling air injection of 9,292 Nm^3/h is required to reduce the gas temperature from 1000 °C to 800 °C in order to maintain safe furnace operation. The findings demonstrate that precise control of calcine carbon content and optimized cooling air design are essential for improving operational safety and efficiency in nickel smelting. The developed model provides a quantitative basis for designing safer and more efficient industrial off-gas control systems.

Keywords: Nickel matte; Mass and energy balance; Calcine carbon; Exhaust gas; Cooling air.

1. Introduction

The rapidly increasing global demand for nickel, driven primarily by the battery and stainless steel industries, has positioned laterite ores as the main source of primary nickel production, gradually replacing declining sulfide ore reserves [1], [2]. Among the various available processing routes, the Rotary Kiln–Electric Furnace (RKEF) process remains the dominant pyrometallurgical technology, despite being highly energy-intensive and requiring comprehensive thermal evaluations at both system and particle scales to achieve optimal operational efficiency [3].

Efforts to improve process performance involve modifying material compositions, including the addition of additives such as calcium carbonate ($CaCO_3$) to enhance mineralogical characteristics and particle growth during reduction [4]. In the context of sustainability, the development of $CaCO_3$ derived from biogenic waste is being explored as a more environmentally friendly alternative to conventional limestone [5].

The utilisation of biomass through pyrolysis is also emerging as a sustainable process engineering strategy. Agricultural residues, such as corn cobs, can be converted into value-added

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liquid and gaseous products through controlled pyrolysis [6]. Beyond serving as an alternative carbon source, biomass residues in the form of pozzolanic materials have been shown to influence the stability and structural characteristics of composite materials [7]. Understanding the thermochemical conversion of biomass and high-temperature gas-phase behavior is relevant for optimizing industrial off-gas management systems in high-temperature metallurgical operations such as nickel smelting.

From a fundamental perspective, excessive carbon monoxide formation is frequently associated with the reverse Boudouard reaction ($C + CO_2 \rightleftharpoons 2CO$) [8], [9]. The efficiency of this high-temperature reaction is influenced by material physical parameters and pretreatment conditions. The use of subcritical water environments and controlled kinetic parameters has been reported to improve the processing efficiency of complex materials [10], while variables such as particle size and reaction kinetics remain critical factors governing phase interactions in dynamic systems [11].

Ensuring the stability of complex industrial systems requires a systematic multi-variable optimization framework supported by predictive modeling. Structured process parameter optimization principles, as applied in various engineering domains, including pharmaceutical formulation development [12]. Emphasise the importance of rigorous experimental design in enhancing industrial reliability. With advancements in equilibrium constant modeling and multilevel factorial optimization, the predictive accuracy of electric furnace operations can be significantly improved [13], [14].

Despite extensive research on RKEF process optimization, industrial data–based case studies specifically addressing the influence of carbon content fluctuations on cooling air requirements remain limited. This gap restricts the development of predictive safety and emission control strategies in industrial electric furnace operations. Therefore, this study focuses on mass and energy balance modeling to determine the optimal cooling air volume required at a target temperature of 800 °C. Utilising actual operational data from an electric furnace with a capacity of approximately 150 tons per hour, this research aims to establish a quantitative relationship between calcine carbon content and gas emission loads as a foundation for safer and more efficient off-gas control strategies.

2. Materials and Methods

This study employed a quantitative approach using mathematical modeling of mass and energy balances based on industrial operational data. The research stages consisted of data collection, compositional analysis, thermodynamic modeling, and optimization through regression analysis.

2.1 Materials

The primary material analysed was calcined saprolite-type nickel laterite ore sourced from a mining region in South Sulawesi, Indonesia. The average chemical composition of the calcine consisted of nickel (1.96 per cent), iron (23.21 per cent), carbon (1.96 per cent), silica (39.97 per cent), and magnesium oxide (18.42 per cent). In addition, a commercial electrode paste manufactured in Germany, containing approximately 90 per cent carbon, was used as both a reducing agent and an electrical conductor in the furnace.

2.2 Experimental Setup and Data Acquisition

The evaluation was conducted on an industrial-scale electric furnace unit operating at an approximate feed capacity of one hundred and fifty tons per hour. Monitoring instruments included industrial K-type thermocouples and a portable infrared thermography camera (FLIR Systems, United States) for surface temperature verification. Gas flow rates within the exhaust gas ducting system were measured using a Type-S pitot tube (Dwyer Instruments, United States). This study used secondary operational data obtained from archived industrial monitoring records collected during the 2017 operational period.

2.3 Characterisation and Analytical Methods

Calcine, nickel matte, and slag samples were analysed using standardised industrial laboratory procedures. Sample preparation involved size reduction using a jaw crusher, followed by sieving through standard mesh screens. The concentrations of major elements, including nickel, iron, silicon, and magnesium, were determined using X-ray fluorescence spectroscopy (XRF, PANalytical, Netherlands). Carbon and sulfur contents were analysed using a combustion–infrared absorption method with a LECO analyser (LECO Corporation, United States) [13], [15].

2.4 Modeling and Optimization Procedures

Mass balance calculations were developed based on the law of conservation of mass, incorporating the reverse Boudouard reaction ($C + CO_2 \rightleftharpoons 2CO$) occurring in the high-temperature zones of the furnace [1], [8]. Thermodynamic analysis was performed using the heat balance principle, in which the released heat equals the absorbed heat, to determine the thermal load of the exhaust gas [3]. The molar specific heat capacity values of individual gas components were calculated through temperature-dependent polynomial integration based on standard thermodynamic data [16], [17]. Final optimization was conducted by simulating variations in carbon content ranging from 1.7 to 2.5 per cent using linear regression analysis to predict exhaust gas volume and cooling air (gap air) requirements [18], [19].

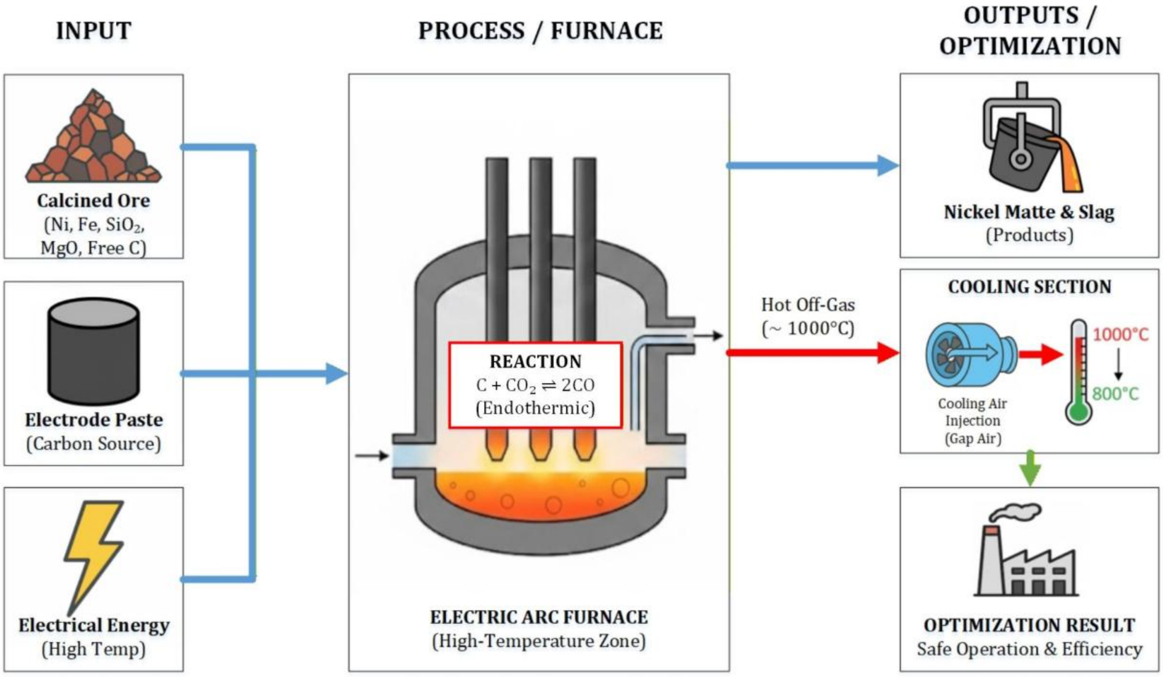


Figure 1. Mass and energy balance flow diagram for the electric furnace smelting process, illustrating inputs, outputs, the primary reverse Boudouard reaction in the high-temperature zone, and the thermodynamic analysis and optimization loop.

Figure 1 illustrates the comprehensive mass and energy balance framework developed for the electric furnace smelting process used in this study. The system boundaries define the material inputs—specifically calcined ore (comprising Ni, Fe, free C, SiO_2, and MgO) and carbonaceous electrode paste—alongside the substantial electrical energy input required to sustain high operating temperatures. Within the furnace's high-temperature zone, these inputs undergo physicochemical transformations, where the endothermic reverse Boudouard reaction $(C + CO_2 \rightleftharpoons 2CO)$ plays a critical role in determining the gas phase composition. The process yields molten nickel matte as the primary product, slag as gangue waste, and a high-enthalpy off-gas stream. Crucially, the diagram highlights the iterative modeling loop employed in this research: by applying thermodynamic analysis based on the heat balance principle, the model simulates variations in input carbon content (ranging from 1.7% to 2.5%) to accurately predict the resulting off-gas volume and determine the necessary cooling air requirements.

3. Results and Discussion

3.1 Thermodynamic and Chemical Characteristics of Off-Gas

Based on mass balance modeling of an industrial-scale electric furnace, the composition of off-gas is strongly influenced by the free carbon content present in the calcine. This carbon undergoes oxidation reactions to form CO and CO_2 gases within the furnace. An increase in carbon content promotes the reverse Boudouard reaction $(C + CO_2 \rightleftharpoons 2CO)$ in high-temperature furnace zones, significantly increasing the proportion and volume of carbon monoxide in the off-gas stream [8], [20].

This phenomenon is of particular concern because CO is highly flammable at elevated temperatures, thereby increasing the risk of explosion within the off-gas handling system if not properly controlled through adequate cooling air injection [16], [17]. In addition, nickel recovery efficiency is influenced by these gas–solid interactions, where metallurgical losses must be minimised through optimal control of furnace atmosphere conditions [4], [21].

3.2 Effect of Carbon Variation on Emission Volume

Simulation results reveal a strong linear relationship between calcine carbon content (%C) and the total volume of off-gas generated in the electric furnace. A comparison between baseline operating conditions (1.96% carbon) and simulated carbon variations is presented in Table 1. The observed increase in gas volume is consistent with multilevel factorial optimization studies, which demonstrate that the reductant ratio plays a decisive role in determining product yield and selectivity in pyrometallurgical processes [13], [14].

Table 1. Comparison of Off-Gas Volume and Gap Air Requirement at Various Calcine Carbon Contents

Calcine Carbon Content (%)	Off-Gas Volume (Nm^3/h)	Gap Air Volume (Nm^3/h)	Remarks
1,70	46.950,13	9.219,68	Minimum value
1,80	47.062,02	9.247,57	–
1,90	47.173,91	9.275,45	–
1,96	**47.241,04**	**9.292,19**	**Actual condition**
2,20	47.509,58	9.359,11	–
2,50	47.845,25	9.442,77	Maximum value

Based on industrial operational data collected from the electric furnace between January and September 2017, the average calcine carbon content during normal plant operation was approximately 1.96%, which represents the actual baseline condition of the furnace. Using this operational dataset as the reference condition, the developed regression model was applied to simulate variations in calcine carbon content ranging from 1.7% to 2.5% in order to evaluate their influence on off-gas generation and cooling air demand. The results indicate that under actual operating conditions (1.96% carbon), the off-gas volume reaches 47,241.04 Nm^3/h with a corresponding cooling air (gap air) requirement of 9,292.19 Nm^3/h. This linear trend arises from the increased rate of carbon oxidation reactions producing CO and CO_2 within the furnace. These findings reinforce the principle that reductant dosage is a primary determinant of emission load in pyrometallurgical operations [13], [14].

3.3 Model Significance Analysis

Statistical analysis using Design-Expert® 10 software was conducted to evaluate the significance of the developed regression models. Analysis of Variance (ANOVA) confirms that carbon content variation has a highly significant effect on both off-gas volume and cooling air demand, with p-values < 0.0001 [18], [19].

Table 2. Analysis of Variance (ANOVA) Off-Gas Volume

Source	Sum of Squares	df	Mean Square	F Value	p-value (Prob > F)
Model	0,77	2	0,39	7,105E+006	< 0.0001*
A-Carbon Content	*0,77*	*1*	*0,77*	*1,419E+007*	*< 0.0001*
A2	*3,754E-007*	*1*	*3,754E-007*	*6,90*	*0,0341*
Residual	3,809E-007	7	5,441E-008		
Cor Total	0,77	9			

Table 3. Analysis of Variance (ANOVA) Gap Air Volume

Source	Sum of Squares	df	Mean Square	F Value	p-value (Prob > F)
Model	0,048	2	0,024	5,660E+005	< 0.0001*
A-Carbon Content	*0,048*	*1*	*0,048*	*1,130E+006*	*< 0.0001*
A2	*4,720E-007*	*1*	*4,720E-007*	*11,12*	*0,0125*
Residual	2,970E-007	7	4,243E-008		
Cor Total	0,048	9			

Statistical validation conducted via ANOVA tables (Tables 2 and 3) indicates that the developed linear regression models possess an exceptionally high level of confidence. *P*-values of less than 0.0001 signify that the influence of calcine carbon content on both off-gas volume and cooling air demand is not coincidental but statistically significant. The high *F*-values, ranging from 105 to 106, further confirm the numerical stability and robustness of the models for operational forecasting. As established in metallurgical process control literature, the implementation of measured control structures in industrial gas management enhances operational stability through precise and predictive modeling [18], [19].

The coefficient of determination (R^2) of 1.0000 demonstrates that the models explain the entire variability of the observed data. This perfect correlation arises from the deterministic nature of the mass and energy balance–based modeling approach, combined with a relatively narrow range of industrial operational conditions. Therefore, the regression models are appropriate for describing the system behavior within the defined operating window.

Consequently, the following mathematical relationships are validated for emission control prediction in industrial-scale electric furnace units:

- **Volume Off-Gas (Nm^3/h):**

$$y = 1118{,}9x + 45048$$

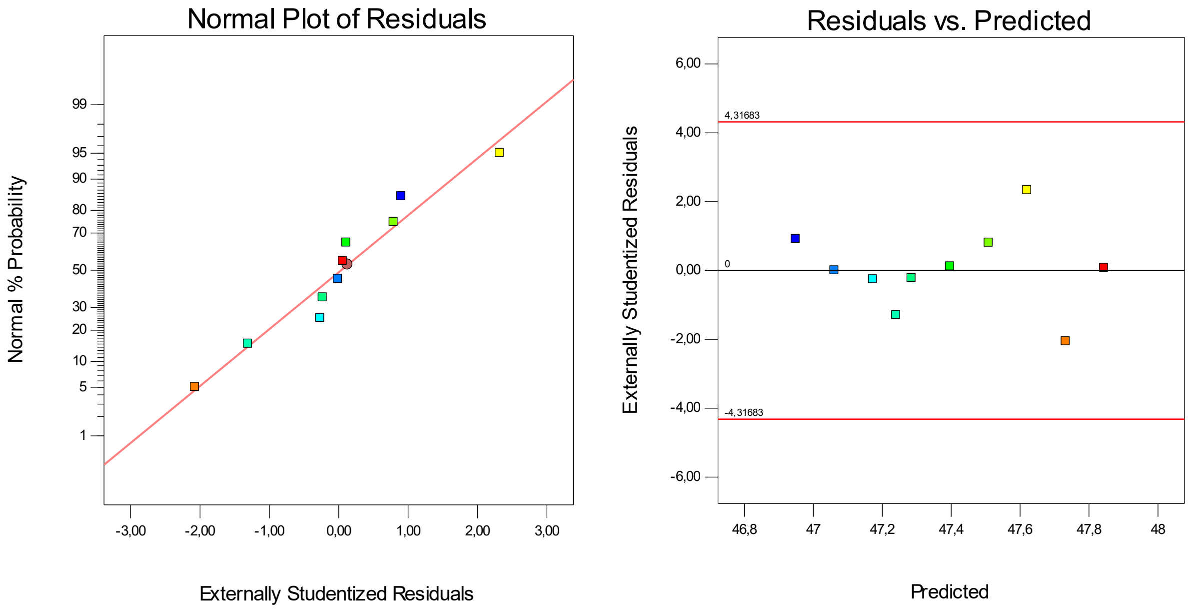
- **Volume Gap Air (Nm^3/h):**

$$y = 278{,}87x + 8745{,}6$$

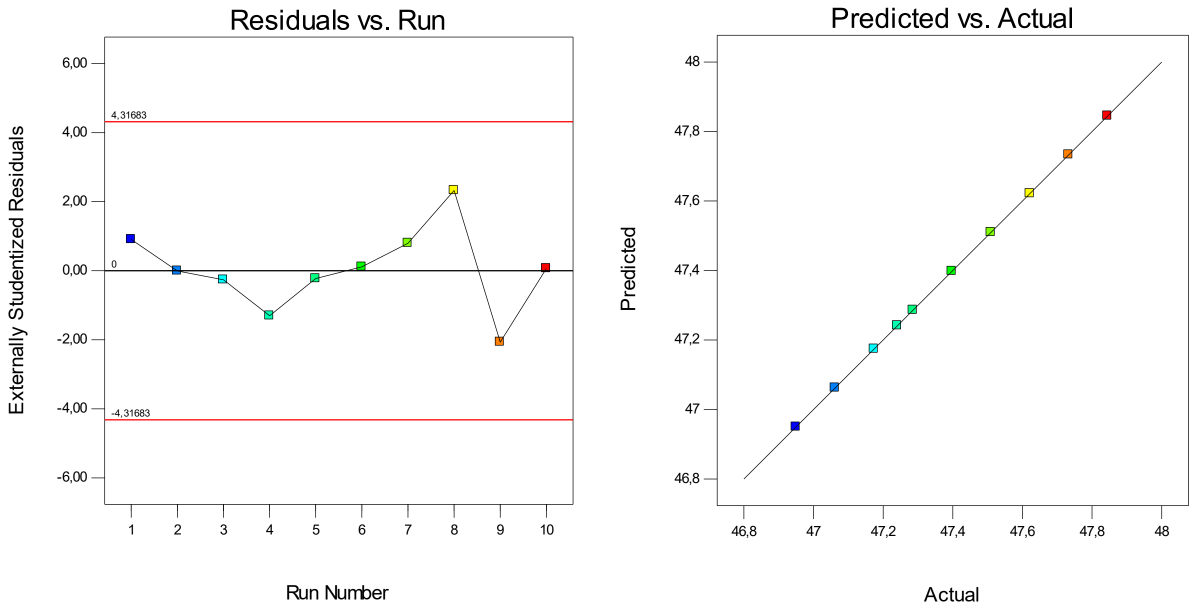
Model accuracy is further substantiated by the Predicted vs Actual plots, which show data points precisely aligned along the primary correlation line, confirming the reliability of the models in responding to field-level carbon fluctuations [13], [14]. An increase in calcine carbon content directly elevates the generation of oxidation product gases (CO and CO_2); consequently, the cooling air (gap air) requirement increases linearly to maintain the target furnace operating temperature of 800 °C.

3.4 Validation of Model Assumptions Using Diagnostic Plots

The reliability of the developed linear regression models was evaluated through a comprehensive set of diagnostic tests to ensure that the fundamental statistical assumptions were satisfied. The diagnostic results for the off-gas volume and gap air volume models are presented in Figure 1 and Figure 2, respectively.

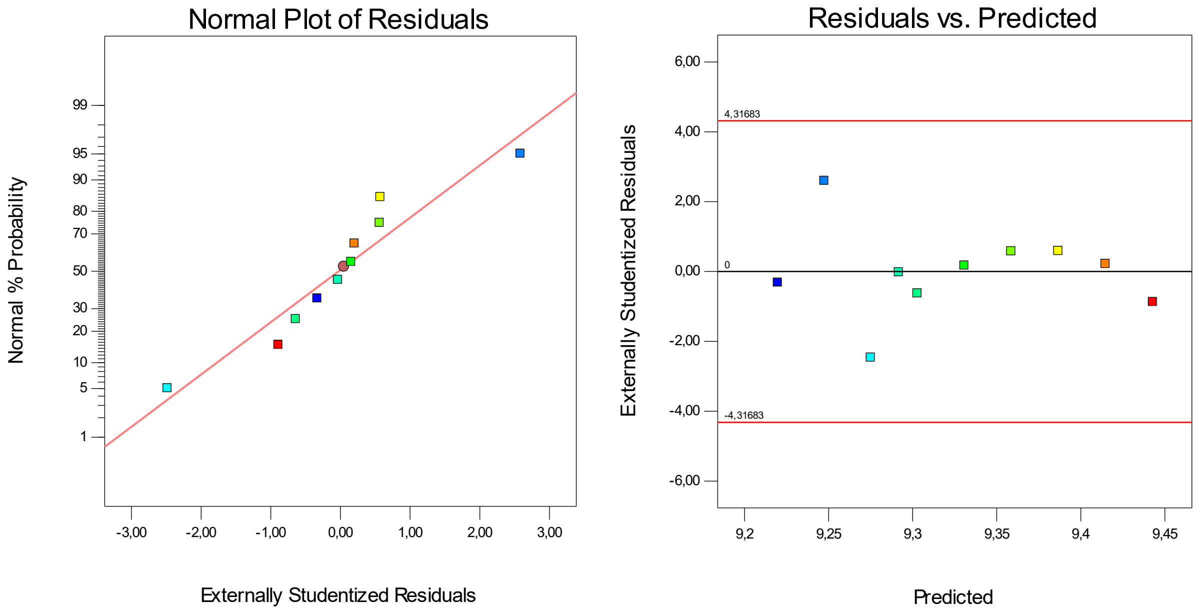


(a) (b)



(c) (d)

Figure 1. Diagnostic panel for the furnace off-gas volume model: (a) Normal plot of residuals; (b) Residuals vs. predicted values; (c) Residuals vs. run order; and (d) Predicted vs. actual values.



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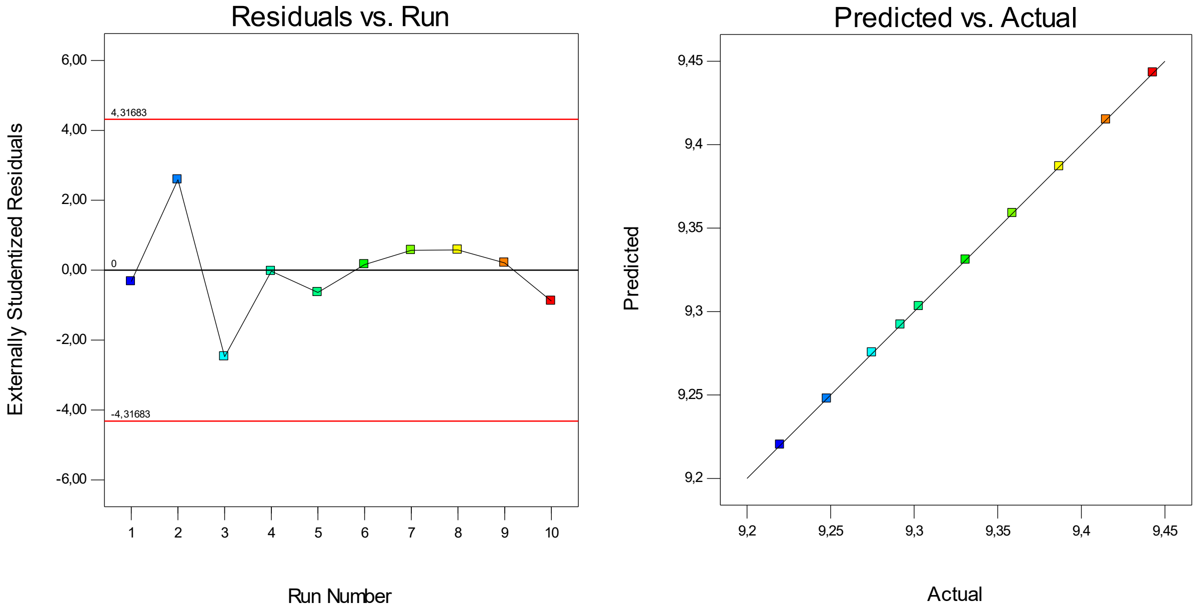

(c) (d)

Figure 2. Diagnostic panel for the furnace gap air volume model: (a) Normal plot of residuals; (b) Residuals vs predicted values; (c) Residuals vs run order; and (d) Predicted vs actual values.

The normal probability plots of the residuals (Figures 1a and 2a) show that the data points are closely distributed along a straight line, indicating that the residuals follow an approximately normal distribution without significant systematic deviation. The predicted versus actual plots (Figures 1d and 2d) demonstrate an exceptionally strong correlation, with an R^2 value of 1.0000, where the observed data are virtually aligned with the primary correlation line [13], [14]

Furthermore, the residuals versus predicted value plots (Figures 1b and 2b) and residuals versus run order plots (Figures 1c and 2c) exhibit a random scatter of points within the control limits. This behavior confirms constant variance (homoscedasticity) and indicates the absence of time-dependent trends or autocorrelation in the operational data. Collectively, these diagnostic results validate the robustness and reliability of the developed models in responding to calcine carbon fluctuations while maintaining stable furnace operation at the target temperature of 800 °C [22], [23].

3.5 Implications for Safety, Environment, and Material Integrity

The target cooling temperature of 800 °C was selected based on operational constraints and material limitations in the off-gas handling system. Temperatures significantly above this level may cause excessive thermal stress and accelerate refractory degradation in the duct system. Conversely, cooling the gas to much lower temperatures may lead to premature condensation of certain gas components and reduce thermal efficiency. Therefore, maintaining the off-gas temperature at approximately 800 °C provides a practical balance between equipment protection and stable operation. Under these conditions, controlled ambient air injection (gap air) functions as an integrated safety barrier that prevents uncontrolled secondary oxidation of CO gas within downstream combustion and gas-handling units [22], [24]. In addition, effective off-gas management minimises the corrosion risk to magnesia–chromite refractory linings caused by prolonged exposure to sulfur-containing species, particularly sulfur dioxide (SO_2), present in the gas stream [25], [26].

Furthermore, this operational strategy contributes to greenhouse gas mitigation efforts and supports carbon neutrality objectives within the metallurgical industry [9], [27]. Routine inspections employing advanced monitoring technologies, including unmanned aerial vehicle–based systems, remain essential to ensure the long-term integrity, safety compliance, and operational reliability of industrial furnace gas-handling systems [23], [28].

4. Conclusion

This study successfully established a quantitative relationship between calcine carbon content and gas emission load in an industrial electric furnace unit. The analysis confirms that calcine carbon content has a highly significant linear effect on off-gas volume and cooling air requirements ($p < 0.0001$). Under actual operating conditions with a carbon content of 1.96 %, the off-gas volume reaches 47,241 Nm^3/h, requiring a gap air injection of 9,292 Nm^3/h to stabilise the gas temperature from 1000 °C to 800 °C. Validation using Design-Expert 10 with a coefficient of determination (R^2) of 1.0000 demonstrates the high predictive accuracy of the developed model for industrial applications. As a recommendation for future work, these mathematical models may be integrated into automated process control systems (PLC/DCS) to enable real-time cooling air regulation based on continuous carbon analysis. Furthermore, extending the model to incorporate variable feed rates and calcine moisture content could further improve energy efficiency and operational stability in off-gas treatment systems.

Author contributions: Conceptualization, S.B. and A.N.L.R.; data curation, M.I.T. and A.N.L.R.; formal analysis, S.B. and F.D.H.; investigation, M.I.T. and A.N.L.R.; methodology, S.B. and A.N.L.R.; project administration, S.B.; resources, S.B.; software, S.B. and E.M.S.E.T.; supervision, S.B.; validation, S.B., A.N.L.R., and M.I.T.; visualization, F.D.H. and E.M.S.E.T.; writing—original draft preparation, A.N.L.R. and M.I.T.; writing—review and editing, S.B. All authors have read and agreed to the published version of the manuscript.

Acknowledgement: The authors gratefully acknowledge the Department of Chemical Engineering, Pattimura University (Unpatti), for providing academic support and research facilities. The authors also appreciate the nickel smelting industry for supplying actual operational data used as the primary basis of this study. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interest: The authors declare no conflicts of interest.

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