Development of PID-BASED Temperature Controller in an Aluminium Extrusion Aging Furnace

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Abstract: *Traditional On-Off control proved inadequate for aluminum extrusion ageing furnace due to temperature oscillations and poor adaptability, necessitating a more robust solution. Hence, this study presents the development of a PID-based temperature controller, aimed at enhancing temperature regulation and energy efficiency. The PID controller was chosen for its ability to deliver continuous, precise regulation, improving system stability and response. The furnace was modeled as a First-Order Plus Dead-Time (FOPDT) system, and multiple PID tuning techniques were explored. Three tuning methods, Ziegler-Nichols, Cohen-Coon, and Quarter Amplitude Damping Ratio (QADR), were implemented and compared. Ziegler-Nichols produced a fast but oscillatory response; Cohen-Coon offered a more balanced performance, while QADR achieved a critically damped response with minimal overshoot and ensured stability. Simulations and experimental validation were conducted in MATLAB using key performance indices, including Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral Time Absolute Error (ITAE), and Integral Time Squared Error (ITSE). Results showed that QADR outperformed the others, delivering the lowest error metrics, reduced overshoot of 109.3399°C, rise time of 0.0363min, and improved settling time of 1.3860min. However, Ziegler-Nichols delivered fastest rise time of 0.0280min, with excessive overshoot of 127.3424°C, posing high risk to furnace temperature sensitivity. Cohen-Coon offered compromise values between speed and damping. Findings support PID control, particularly QADR tuning, as a highly effective solution for industrial furnace regulation, improving stability, energy efficiency, and product quality. The validated model and optimized PID controller provide a reliable solution; future work could explore adaptive tuning techniques, such as machine learning-based optimization.*

Keywords: *Quarter Amplitude Damping Ratio, Cohen-Coon, Ziegler-Nichols, Adaptive Tuning Techniques and Aluminium Extrusion Ageing Furnace.*

1. INTRODUCTION

The aluminum extrusion aging process is a critical stage in producing aluminum extrusions, where the material's mechanical properties are enhanced through a controlled heating and cooling cycle. This process involves heating the extruded aluminum profiles to an elevated temperature, typically between 150°C to 250°C, followed by soaking at the desired temperature and then gradually cooling to room temperature. During the aging process, the microstructure of the aluminum alloy undergoes significant changes, including the precipitation of strengthening phases, which ultimately improve the material's mechanical properties such as strength and hardness [1].

Effective temperature control is paramount in the aluminum extrusion aging process to ensure the desired metallurgical properties are achieved consistently across the extruded profiles. Temperature variations can significantly impact the final product quality, leading to inconsistencies in mechanical properties and dimensional tolerances. Maintaining precise temperature control is particularly crucial

due to the sensitivity of aluminum alloys to thermal treatments, where deviations from the optimal aging temperature or soaking time can result in suboptimal material properties [2].

Traditionally, temperature control in aluminum extrusion aging furnaces has been implemented using simple on-off control systems. These systems operate by switching the heating elements on when the temperature falls below a set point and off when it exceeds the set point, resulting in a binary control action. While on-off control is straightforward and cost-effective, it has several limitations that can compromise temperature stability and uniformity within the furnace chamber [3]. One major drawback is the inherent oscillatory behavior around the set point, leading to temperature overshoots and undershoots, negatively impacting product quality and increased energy consumption. Additionally, on-off control systems cannot adapt to changes in process conditions or disturbances, resulting in suboptimal performance in dynamic operating environments [4], [5], [6].

In recent years, there has been a growing interest in adopting more advanced control techniques, such as Proportional-Integral-Derivative control, to improve temperature regulation in aluminum extrusion aging furnaces. PID control offers advantages over on-off control by providing continuous modulation of the heating elements based on feedback from temperature sensors, enabling smoother and more precise control of the furnace temperature [7]. The PID controller calculates the control signal by considering the current error (the difference between the desired set value (SV) and the present value (PV) temperature), as well as the integral and derivative of the error over time, allowing for efficient correction of deviations from the set point.

Despite the widespread use and proven benefits of PID control in industrial automation, its effective application in aluminum extrusion ageing furnaces requires careful consideration of system-specific dynamics. Challenges such as tuning complexity, robustness against disturbances, and integration with legacy systems present opportunities for innovation rather than limitations. Achieving optimal PID parameters is crucial to ensuring stability, responsiveness, and precision in temperature regulation all of which are vital for product quality in ageing processes [8].

This study aims to develop a PID-based temperature controller suitable for an aluminum extrusion aging furnace; develop a mathematical model that describes the transient response of the temperature of the furnace in response to changes in power supply; estimate the unknown parameters of the developed mathematical model using open-loop response experimental data, design a PID controller using tuning techniques provided by Ziegler-Nichols, Cohen-Coon, and Quarter Amplitude Damping Ratio and to validate the performance of the developed PID controller using simulation-generated data to determine its effectiveness and identify the optimal tuning approach. This finding will contribute to the advancement of temperature control technology in the aluminum extrusion industry, with potential implications for enhancing product quality, process consistency, and energy efficiency. It will also facilitate the adoption of advanced control technologies by industrial practitioners, ultimately leading to improved competitiveness and sustainability in the aluminum extrusion sector.

2. MATERIALS & METHODS

3. DYNAMIC MODEL OF AGING FURNACE

A systematic approach is adopted to derive a mathematical model for the furnace system, starting with the fundamental principles of heat transfer. The model formulation is based on Fourier's Law of Heat Conduction and the First Law of Thermodynamics, which govern how heat energy is distributed and stored within the furnace [9]. Using these principles, the system's behavior is described through differential equations and later transformed into a transfer function representation, which is crucial for control system design and analysis. The final model follows a First-Order Plus Dead-Time (FOPDT) structure, commonly used in thermal process control due to its ability to capture the system's dynamic response accurately. The final first-order plus dead-time (FOPDT) model is given as

$$\frac{T_s}{V_s} = \frac{Ke^{-\theta s}}{\tau s + 1} \qquad (1)$$

$\frac{T_s}{V_s}$ is the transfer function of the Aging furnace (plant) G_s, Where K is the Process gain (°C/V), τ is time constant (s), and θ is the dead time (s).

4. TRANSFER FUNCTION EQUATION FROM FIRST PRINCIPLE

The closed loop block diagram for the temperature-based controller using equation (1) which represents the plant modeled as a First-Order Plus Dead-Time (FOPDT) system with the required transfer function of the system is shown in Figure1:
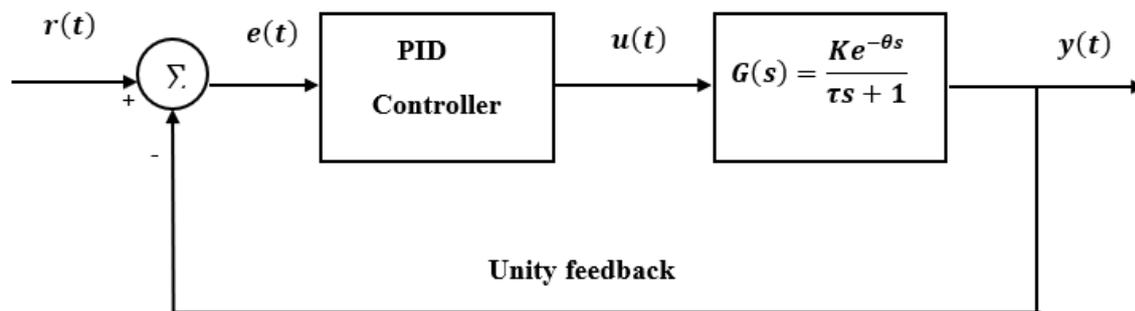

Figure 1. *PID Controller Block Diagram Representation*

The relationship between the output $Y(s)$ and the reference input $R(s)$ for the plant (furnace) is given as :

$$\frac{Y(s)}{R(s)} = \frac{Ke^{-\theta s}(K_p s + K_i + K_d s^2)}{\tau s + 1 + Ke^{-\theta s}(K_p s + K_i + K_d s^2)} \tag{2}$$

This expression represents the closed-loop transfer function of the system, explicitly showing the contributions of the PID controller parameters (K_p, K_i, K_d) and the plant parameters (K, τ, and $e^{-\theta s}$). The derived transfer function provides a comprehensive understanding of how the PID controller and the FOPDT modelled plant interact in a closed-loop system. This formulation is crucial for analyzing system behavior and guiding the tuning of controller parameters to achieve desired performance.

5. SYSTEM OPERATION AND CONTROL FLOW

The system operates in a closed-loop configuration, where the temperature sensor continuously measures the furnace temperature and sends this data to the Arduino. The Arduino, in turn, communicates with MATLAB, where the PID controller processes the data and determines the required heating power. Based on this calculation, the Arduino sends an activation signal to the opto-isolator, which triggers the TRIAC to regulate power delivery to the furnace. The energy meter records power consumption, and MATLAB logs all performance data for analysis. By fine-tuning the PID parameters, the system ensures stable temperature control with minimal overshoot and steady-state error. This approach optimizes energy efficiency and improves the quality of aluminum aging by maintaining a precise thermal profile. The System set-up is shown in Figure 2.
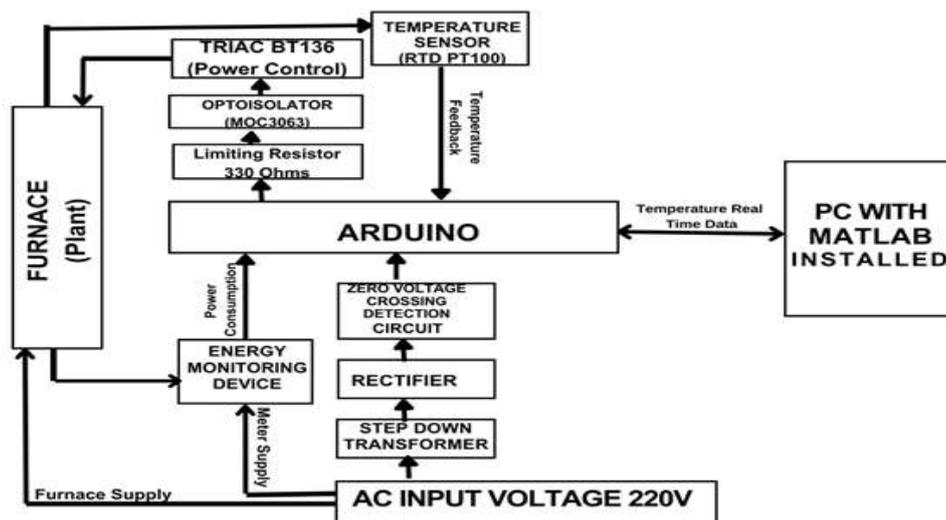

Figure 2: *System set-up*

This system setup integrates precise temperature sensing, intelligent control algorithms, and efficient power regulation to enhance the performance of an aluminum extrusion aging furnace. The combination of Arduino, MATLAB, and a TRIAC-based switching system ensures accurate and reliable temperature management. The use of an opto-isolator guarantees electrical safety, while real-time monitoring and data logging enable performance evaluation and optimization.

6. PROCEDURE

6.1 Model Identification

The complete setup is configured as illustrated in Figure 2. A simulation is carried out using the on/off controller design, and the scope data is recorded and transferred to the System Identification Toolbox. The recorded data is then fitted to a model for parameter estimation and to evaluate the model's goodness of fit

6.2 Closed Loop Controller Design

To achieve precise temperature regulation in the aluminum extrusion aging furnace, a Proportional-Integral-Derivative (PID) controller was designed and implemented using experimental data obtained from the model identification.

6.3 System Modeling and Parameter Estimation

The furnace system was modeled as a First-Order Plus Dead-Time (FOPDT) system, based on data collected from open-loop tests. The experimental setup (described in figure 3) was used to obtain the step response, and the key system parameters such as process gain, time constant and dead time were estimated using MATLAB's System Identification Toolbox. Using curve-fitting techniques, the best-fit model was derived, and the estimated transfer function was used as the basis for controller design.

6.4 PID Parameter Optimization and Deployment

To determine the optimal PID controller parameters, three standard tuning methods were applied:

6.5 Ziegler-Nichols Ultimate Gain Method

The proportional gain (K_p) was gradually increased in an open-loop test until the system reached sustained oscillations.

The critical gain (K_u) and oscillation period (T_u) were recorded.

These values were used to compute the PID parameters using Ziegler-Nichols tuning rules.

6.6 Cohen-Coon Tuning Method

This method used the identified process parameters (K_p, τ, t_d) to calculate tuning constants. Cohen-Coon tuning was selected due to its ability to provide faster response with reduced steady-state error compared to Ziegler-Nichols.

6.7 Quarter Amplitude Damping Ratio Method

This method was applied to achieve a critically damped response, ensuring minimal overshoot. The tuning parameters were computed using the quarter amplitude decay equation.

Each tuning method was implemented separately, and the PID parameters were applied to the furnace control system for comparison.

6.8 Simulation and Performance Evaluation

The tuned PID controllers were simulated in MATLAB Simulink to analyze their performance under closed-loop conditions. The performance metrics such as rise time, settling time, over shoot, steady state error and integrated error metrics (ISE, IAE, ITAE, ITSE) were evaluated for each tuning method. The PID tuning method that yielded the best trade-off between response speed, stability, and minimal overshoot was selected for final implementation in the furnace control system.

6.9 Performance Evaluation of The Controlled System

The tuned parameters were entered into MATLAB Simulink block diagrams. The controller performance is measured in terms of integrated squared error (ISE), integrated absolute error (IAE), in

tegrated time squared error (ITSE), and integrated time absolute error (ITAE).

ISE**:** This metric evaluates the overall error magnitude by squaring the error signal and integrating it over time. It penalizes large deviations more significantly.

$$ISE = \int_0^\infty e^2(t)dt \qquad (3)$$

Integrated Absolute Error (IAE)**:** Unlike ISE, IAE considers the absolute value of the error, preventing excessive weighting of large errors and making it useful for systems where small persistent errors are more critical.

$$IAE = \int_0^\infty |e(t)| \, dt \qquad (4)$$

Integrated Time Square Error (ITSE): modifies ISE by adding a time factor, giving more weight to errors occurring later in the response. This helps improve long-term performance by minimizing sustained errors.

$$ITSE = \int_0^\infty t\, e^2(t)dt \qquad (5)$$

Integrated Time Absolute Error (ITAE): Similar to ITSE, ITAE multiplies the absolute error by time, prioritizing early error correction and reducing long-term deviations for a smoother response.

$$ITAE = \int_0^\infty t\, |e(t)| \, dt \qquad (6)$$

The output is linked to a scope to view the plot of the simulation results such as the rise time, settling time, and peak overshoot ratio (POR).

7. RESULTS AND DISCUSSION

The experimental approach was used to model the aluminum extrusion aging furnace and extract key system parameters that form the basis for controller tuning.

The experimental setup, as previously described, was implemented with the furnace operating in open-loop mode under constant AC voltage (230V, 50Hz). A temperature sensor (RTD PT100) was positioned inside the furnace to measure the internal temperature over time. Data acquisition was carried out using an Arduino microcontroller, which transmitted temperature readings to MATLAB via serial communication for analysis.

The furnace was initially at room temperature (approximately 25°C), and power was supplied to the heating element without any active feedback control. The system's temperature response was monitored until it reached a steady-state condition.

The temperature-time response obtained from this experiment is presented in Figure 3, showing the furnace's thermal behavior in an open-loop configuration.
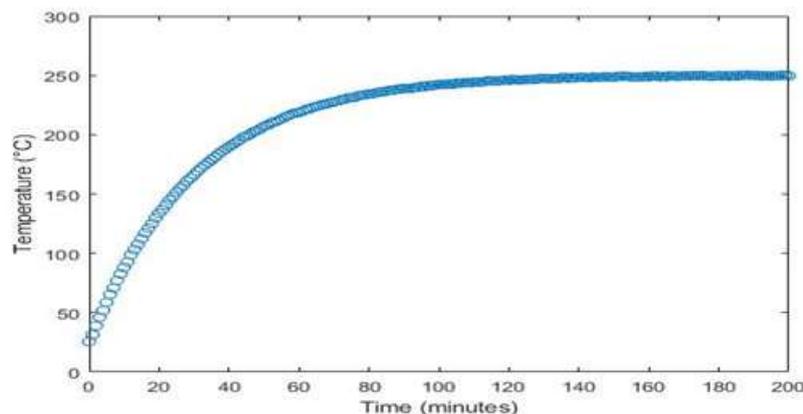

Figure 3. *Open-loop response of the aluminum aging furnace*

The open-loop temperature response of the furnace exhibited a gradual increase from 25°C to approximately 250°C over 200 minutes before reaching steady-state conditions. This slow thermal response highlights the system's inherent heat transfer characteristics and the need for an optimized controller to enhance performance.

The recorded temperature data was imported into MATLAB's System Identification Toolbox, where curve-fitting techniques were applied to estimate the system's transfer function. The identified first-order plus dead-time (FOPDT) model aligns well with typical thermal system behavior and is mathematically represented as [10], [11]:

From equation 1. the plant equation is defined as;

$$\frac{T_s}{V_s} = \frac{Ke^{-\theta s}}{\tau s + 1} \tag{1}$$

where:

K = process gain (°C/min), τ = time constant (min), and θ = Dead time (min)

From the model fitting results, the estimated system parameters were:

Process Gain (K) = 1.086 °C/min, time Constant(τ) = 30.3054 min, and dead time (θ)= 0.1535 min

Substitute the parameter values into equation 4.1

Therefore,

$$\frac{T_s}{V_s} = \frac{1.086e^{-0.1535s}}{30.3054s + 1} \tag{7}$$

The fitted model's response, along with the experimental data, is shown in Figure 4, demonstrating a close match between the model and real system behavior.
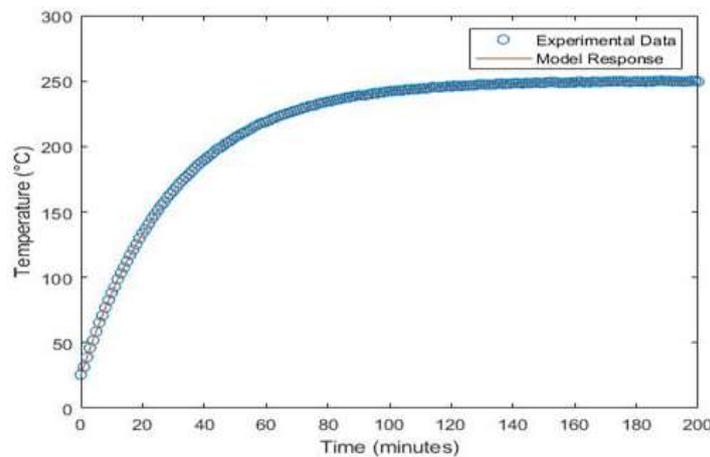

Figure 4. *Model fitting showing the system identification data*

7.1 Model Validation and Considerations

The estimated model parameters align well with expected thermal dynamics for an aluminum aging furnace [12], [13]. However, potential discrepancies may arise due to:

1. Measurement inaccuracies from sensor noise or thermal lag

2. External disturbances, such as airflow or heat loss, that were not accounted for

3. Nonlinearities in the heating system that may require advanced modeling approaches

To ensure robustness, the model was validated against multiple datasets, confirming its reliability for PID controller tuning and performance analysis.

This identified model serves as the foundation for designing an optimized PID temperature controller [14], [15], [16], as detailed in the next section.

7.2 Determination of PID Controller Tuning Parameters

The PID controller tuning parameters for Ziegler-Nichols, Cohen-Coon, and quarter amplitude damping ratio are determined and presented in Table 1.

The Table 1 outlines the tuning parameters obtained using different PID controller tuning techniques, namely Ziegler-Nichols, Cohen-Coon, and the Quarter Amplitude Damping Ratio method.

Table 1. *PID Controllers Tuning Parameters*

PID Tuning Technique	Controller Gain	Integral Gain	Derivative Time
Ziegler-Nichols	236.9151792	0.307	0.07675
Cohen Coon	245.6531552	0.382924524	0.05674183
Quarter Amplitude Damping Ratio	218.1539403	0.307	0.07675

These parameters, including the controller gain, integral time, and derivative time, play crucial roles in shaping the performance of the PID controller. The controller gain determines the proportional response of the controller to the error signal, affecting the system's responsiveness and steady-state error. A higher controller gain typically leads to faster response but may also amplify oscillations and introduce instability if set too high.

The integral time, also known as the reset time, influences the controller's ability to eliminate steady-state error by integrating the error signal over time. A longer integral time increases the controller's ability to correct for sustained errors but may lead to sluggish response and overshoot if set too high Similarly, the derivative time, or the rate time, governs the controller's response to the rate of change of the error signal. It contributes to damping oscillations and improving stability, particularly in systems with significant inertia or disturbances. However, excessive derivative action can amplify noise and lead to instability. [17], [18].

Considering the impact of these tuning parameters on controller performance, we can make predictions about the expected behavior of each tuning method. For instance, the Ziegler-Nichols method typically yields aggressive tuning parameters, resulting in a fast response but potentially high overshoot and oscillations. Conversely, the Quarter Amplitude Damping Ratio method tends to prioritize stability over speed, leading to slower but more damped responses with reduced overshoot The Cohen-Coon method, falling between these extremes, may offer a balanced compromise between response speed and stability, depending on the specific process dynamics and tuning requirements.

In summary, the choice of the PID controller tuning method and the resulting tuning parameters significantly influence the controller's performance in terms of rise time, settling time, overshoot, and stability. While each tuning method offers distinct advantages and trade-offs, the selection should be guided by a thorough understanding of the system dynamics, performance requirements, and tuning objectives, ensuring optimal controller performance and stability.

7.3 Ziegler Nichols closed loop simulation

The closed loop simulation for Ziegler Nichols was set up in Simulink Environment. Figure 5. shows the step response plot of Ziegler Nichol's Tuned PID controller as displayed by MATLAB. The MATLAB output further showed that the system has a rise time of 0.0280 minutes, a transient time of 1.5958 minutes, a settling time of 1.6462 minutes, a minimum settling temperature of 201.7308°C, a maximum settling temperature of 568.3561°C, an overshoot of 127.3424°C; no undershoot; a peak temperature of 568.3561°C; with a peak time of 0.3070 minutes.

According to the MATLAB output, several key performance metrics are provided, offering insights into the dynamic behavior of the controlled system. The rise time of 0.0280 minutes denotes the time taken for the system's output to rise from 10% to 90% of its final value after a step change in the input. It serves as a measure of the controller's speed of response and is indicative of how quickly the system reaches its new set point the transient time, also known as the settling time, represents the duration for the system's output to reach and remain within a specified tolerance band around the final set point. In this case, a transient time of 1.5958 minutes suggests that the system settles to its new set point relatively quickly after the input change. Similarly, the settling time of 1.6462 minutes indicates the time taken for the system's output to stabilize within the specified tolerance band, further highlighting the controller's ability to regulate the system effectively.

The description also includes information about the temperature range observed during the settling process. The minimum settling temperature of 201.7308°C and the maximum settling temperature of 568.3561°C provide insights into the system's thermal behavior and the extent of temperature variation experienced during the transient period. The presence of an overshoot of 127.3424°C signifies that the system's output briefly exceeds the set point before settling down, which could potentially lead to process variability or instability if excessive the peak temperature in the aluminum ageing process

significantly influences the material's microstructural evolution and mechanical properties. During ageing, aluminum alloys undergo precipitation hardening, a crucial heat treatment step that involves the formation of fine precipitates within the alloy matrix. The peak temperature directly affects the kinetics and morphology of precipitate formation, impacting the alloy's final strength, hardness, and other mechanical properties. An excessively high peak temperature can lead to coarsening of precipitates, reducing their effectiveness in strengthening the alloy and potentially causing overshooting. Conversely, a lower peak temperature may result in incomplete precipitation or insufficient strengthening. Therefore, precise control of the peak temperature is essential to achieve the desired balance between strength and ductility in the aged aluminum alloy, ensuring optimal performance in its intended application [19].
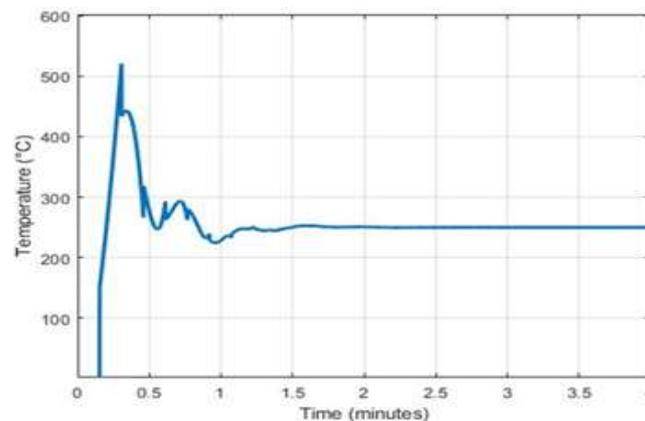

Figure 5. *Step Response of Ziegler Nichol's Tuned PID Controller*

The description also includes information about the temperature range observed during the settling process. The minimum settling temperature of 201.7308°C and the maximum settling temperature of 568.3561°C provide insights into the system's thermal behavior and the extent of temperature variation experienced during the transient period. The presence of an overshoot of 127.3424°C signifies that the system's output briefly exceeds the set point before settling down, which could potentially lead to process variability or instability if excessive the peak temperature in the aluminum ageing process significantly influences the material's microstructural evolution and mechanical properties. During ageing, aluminum alloys undergo precipitation hardening, a crucial heat treatment step that involves the formation of fine precipitates within the alloy matrix. The peak temperature directly affects the kinetics and morphology of precipitate formation, impacting the alloy's final strength, hardness, and other mechanical properties. An excessively high peak temperature can lead to coarsening of precipitates, reducing their effectiveness in strengthening the alloy and potentially causing overshooting. Conversely, a lower peak temperature may result in incomplete precipitation or insufficient strengthening. Therefore, precise control of the peak temperature is essential to achieve the desired balance between strength and ductility in the aged aluminum alloy, ensuring optimal performance in its intended application [19].

Interestingly, the absence of undershoot indicates that the system's output does not dip below the set point during the transient response, suggesting effective control action by the PID controller. The peak temperature of 568.3561°C corresponds to the maximum temperature reached during the transient period, occurring at a peak time of 0.3070 minutes. These metrics provide valuable insights into the dynamic behavior of the controlled system and the performance of the PID controller in achieving and stabilizing around the desired set point. [20].

In agreement with [21], [22], the reported rise time, settling time, overshoot, and other performance metrics reflect the dynamic response characteristics of a well-tuned PID controller operating in a feedback loop. However, it's essential to interpret these results in the context of the specific system dynamics and tuning objectives to ensure optimal performance and stability.

7.4 Cohen-coon Closed Loop Simulation
The closed loop simulation for Ziegler Nichols was set-up in Simulink Environment as shown in Figure

6. Figure 6 shows the step response plot of Cohen-Coon's Tuned PID controller as displayed by MATLAB. The MATLAB output further showed that the system has a rise time of 0.0431 minutes, a transient time of 1.4317 minutes, a settling time of 1.6147 minutes, a minimum settling temperature of 184.1212°C, a maximum settling temperature of 528.7912°C, an overshoot of 111.5165°C; no undershoot; a peak temperature of 528.7912°C; with a peak time of 0.3070 minutes.
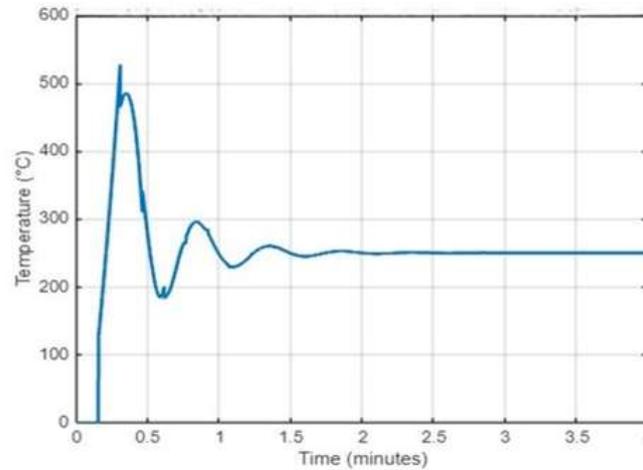

Figure 6. *Cohen Coon's Step Response Tuned PID Controller*

The rise time, a key parameter characterizing the controller's speed of response, is reported as 0.0431 minutes. Comparing this value with the previously discussed Ziegler-Nichol's settings, the Cohen-Coon tuned controller exhibits a marginally slower rise time, suggesting a slightly more gradual response to changes in the setpoint. This difference may arise from the distinct tuning methods employed by the two approaches, with Cohen-Coon tuning typically yielding smoother and more conservative responses compared to the often more aggressive Ziegler-Nichol's method.

Furthermore, the transient time and settling time of the Cohen-Coon tuned controller are reported as 1.4317 minutes and 1.6147 minutes, respectively. These values, while marginally longer than those obtained with Ziegler-Nichol's tuning, indicate that the Cohen-Coon tuned controller takes a slightly extended duration to settle around the new setpoint [23]. This characteristic aligns with the general behavior of Cohen-Coon tuning, which prioritizes stability and robustness over aggressive response. The observed temperature ranges during the settling process, with minimum and maximum settling temperatures of 184.1212°C and 528.7912°C, respectively, suggests effective control action by the Cohen-Coon tuned controller in regulating the system's temperature within an acceptable tolerance band.

Regarding overshoot and undershoot, the Cohen-Coon tuned controller exhibits an overshoot of 111.5165°C without any undershoot. This behavior indicates that the controller achieves effective control without oscillations or excessive deviation from the setpoint, similar to the Ziegler-Nichols tuned controller. However, it's noteworthy that the Cohen-Coon tuned controller achieves a slightly lower minimum settling temperature compared to its Ziegler-Nichols counterpart. This difference in performance metrics may stem from the inherent trade-offs associated with different tuning methods, highlighting the importance of selecting the most suitable tuning approach based on specific control objectives and system dynamics [24].

Despite these variations in performance metrics, both the Cohen-Coon and Ziegler-Nichols tuned controllers demonstrate effective control of the system, achieving the desired temperature setpoint within an acceptable timeframe and with minimal deviation. The similarities and differences observed between the two tuning methods underscore the importance of considering various factors, including system dynamics, performance requirements, and tuning objectives, when selecting an appropriate control strategy.

7.5 Quarter Amplitude Damping Ratio Closed Loop Simulation

The closed loop simulation for quarter amplitude damping ratio (QADR) was set up in Simulink Environment. Figure 7 shows the step response plot of the quarter amplitude damping ratio (QADR)'s

Tuned PID controller as displayed by MATLAB. The MATLAB output further shows that the system has a rise time of 0.0363 minutes, a transient time of 1.3825 minutes, a settling time of 1.3860 minutes, a minimum settling temperature of 224.3012ºC, a maximum settling temperature of 523.3496ºC, an overshoot of 109.3399ºC; no undershoot; a peak temperature of 523.3496ºC; with a peak time of 0.3070 minutes.
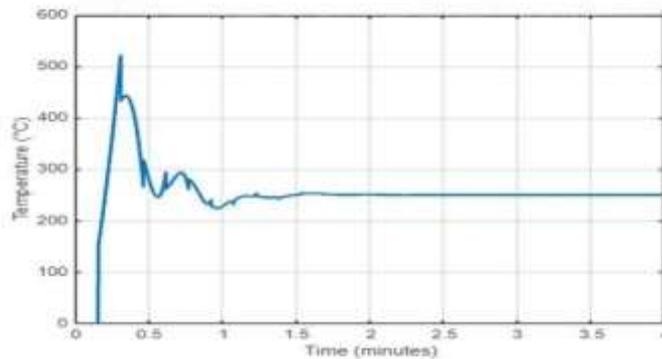

Figure 7. *QADR's Step Response Tunned Parameters*

According to the MATLAB output, the system exhibits a rise time of 0.0363 minutes, indicating the time taken for the system's output to rise from 10% to 90% of its final value after a step change in the input [25].

Compared to the previously discussed Ziegler-Nichols and Cohen-Coon tuned controllers, the QADR-tuned controller demonstrates a rise time that falls between the values obtained from the other two tuning methods. This suggests a moderate response speed, potentially striking a balance between aggressive control action and stability, as typically observed with QADR tuning.

Similarly, the transient time and settling time of the QADR-tuned controller are reported as 1.3825 minutes and 1.3860 minutes, respectively. These values align closely with those obtained from the Cohen-Coon tuned controller, indicating a relatively rapid settling around the new setpoint. However, both the transient and settling times of the QADR-tuned controller are slightly shorter than those obtained with Ziegler-Nichol's tuning. This suggests that the QADR-tuned controller may exhibit a more aggressive response to setpoint changes compared to Ziegler-Nichol's tuning, potentially resulting in quicker stabilization of the controlled system [26].

The minimum and maximum settling temperatures of 224.3012°C and 523.3496°C, respectively, reflect the temperature range experienced during the transient period. Notably, the QADR-tuned controller achieves a lower minimum settling temperature compared to both Ziegler-Nichols and Cohen-Coon tuning methods, indicating a potentially more conservative control approach. The overshoot of 109.3399°C and the absence of undershoot suggest effective control action by the QADR tuned controller, with minimal oscillations or deviation from the setpoint.

Furthermore, the peak temperature of 523.3496°C occurs at the same peak time of 0.3070 minutes as observed with the Ziegler-Nichols and Cohen-Coon tuned controllers. This consistency in peak time suggests that all three tuning methods achieve the maximum temperature at a similar rate. Overall, while the QADR tuned controller exhibits performance metrics that differ slightly from those obtained with Ziegler-Nichols and Cohen-Coon tuning, it demonstrates effective control of the system with characteristics that may be advantageous depending on specific control objectives and system requirements.

However, the overall system response metrics for different PID tuning methods as explained is presented in Table 2:

Table 2. *System Response Metrics for PID Tuning Methods*

PID Tuning Technique	Rise Time (min)	Settling Time (min)	Peak Temp (°C)	Overshoot (°C)
Ziegler-Nichols	0.0280	1.6462	568.3561	127.3424
Cohen Coon	0.0431	1.6147	528.7912	111.5165
Quarter Amplitude Damping Ratio	0.0363	1.3860	523.3496	109.3399

7.6 Performance Evaluation of Controller Tuning Techniques

To evaluate the performance of the three controller tuning techniques namely, Ziegler Nichol's first method, Cohen Coon and quarter amplitude damping ratio, the integral absolute error (IAE), integral squared error (ISE), the integral of time absolute error (ITAE) and the integral of time squared error (ITSE) were determined for each tuning technique and presented in Table 3.

Table 3. *Performance Evaluation of Controller Tuning Techniques*

PID Controller Tuning Technique	IAE	ISE	ITAE	ITSE
Ziegler Nichols	104.079	18203.2291	832843.4779	388481191.5844
Cohen Coon	110.1775	19350.9478	881640.7177	412975039.2
Quarter Amplitude Damping Ratio	92.8653	16377.7688	743108.3041	349523433.5

Each tuning technique, including Ziegler-Nichols, Cohen coon, and Quarter Amplitude Damping Ratio (QADR), is evaluated against these criteria. Starting with Ziegler-Nichol's tuning, the results indicate an IAE of 104.0794, an ISE of 18203.2291, an ITAE of 832843.4779, and an ITSE of 388481191.5844. Comparatively, Cobb-Cohen tuning shows slightly higher values across all indices, with an IAE of 110.1775, an ISE of 19350.9478, an ITAE of 881640.7177, and an ITSE of 412975039.2. On the other hand, the Quarter Amplitude Damping Ratio (QADR) method demonstrates the lowest values among the three techniques, indicating superior performance, with an IAE of 92.8653, an ISE of 16377.7688, an ITAE of 743108.3041, and an ITSE of 349523433.5.

Comparing these results, it's evident that the QADR tuning method outperforms both Ziegler-Nichols and Cobb-Cohen methods across all evaluated performance indices. The QADR method consistently yields lower values for IAE, ISE, ITAE, and ITSE, indicating better control performance in terms of accuracy, stability, and robustness. These findings align with previous studies that have also highlighted the effectiveness of QADR tuning in achieving optimal controller performance.

While Ziegler-Nichols and Cobb-Cohen methods have been widely used and studied, especially in industrial applications, their performance might be suboptimal compared to more advanced tuning methods like QADR. However, it's essential to consider the specific dynamics and requirements of the control system when selecting a tuning technique. Further research could delve into the comparative analysis of various tuning methods across different process models and control objectives to provide deeper insights into their effectiveness. Overall, the results presented in Table 3 underscore the importance of selecting an appropriate tuning method tailored to the specific control system to achieve optimal performance. The superior performance of the QADR method suggests its potential for widespread adoption in industrial control applications, offering improved control accuracy, stability, and efficiency.

7.7 Validation of Controller Performance Error Analysis

Figure 8 shows the plot of simulation and validation data acquired from the prototype after implementing the designed PID controller with Ziegler Nichols Tuning Parameters. The evaluation of the live performance of the PID controller through error analysis, particularly focusing on Integral Absolute Error (IAE), Integral Square Error (ISE), Integral of Time Absolute Error (ITAE), and Integral Time Squared Error (ITSE), serves as a critical aspect of the validation process. These metrics provide insights into the deviation between the experimental validation data and the simulated data, thereby offering a comprehensive understanding of the controller's effectiveness in real-world scenarios. In the context of the provided values, where IAE is reported as 0.15102, ISE as 0.01272, ITAE as 0.20677, and ITSE as 0.061933, it's evident that the errors between the experimental and simulated data are relatively small, indicating a reasonably good agreement between the two datasets.

A low value of IAE suggests that the absolute error between the experimental and simulated data over the entire time span is relatively small, signifying good accuracy in tracking the setpoint. Similarly, the low value of ISE indicates minimal squared error between the datasets, reflecting precise control performance with minimal fluctuations. Additionally, ITAE considers the time-weighted absolute error, where the reported value being relatively small implies efficient tracking of the setpoint over time. Lastly, ITSE reflects the integral of the squared error over time, and the observed small value indicates excellent control performance with minimal oscillations or overshoot.
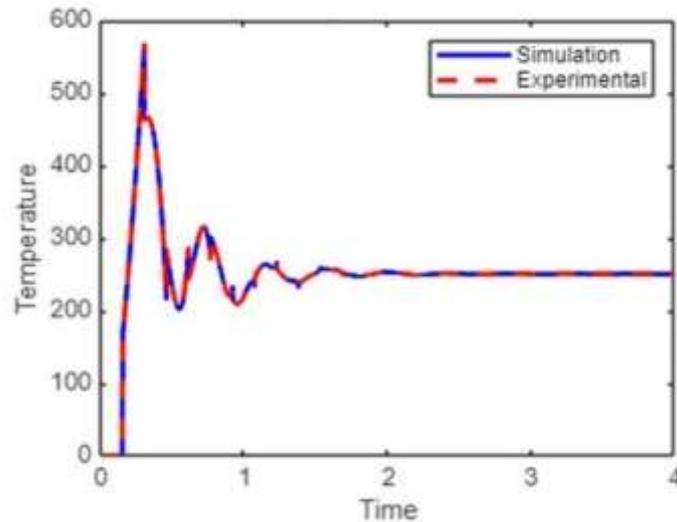
Figure 8. *Validation of Ziegler Nichols Closed-loop simulation*

The agreement between the experimental validation data and the simulated data, as indicated by the low error values across all metrics, validates the efficacy of the PID controller in accurately regulating the system in real time. This finding aligns with [27], which have emphasized the importance of error analysis in validating control system performance. By providing quantitative measures of the discrepancies between simulated and experimental data, error analysis offers valuable insights into the controller's robustness, responsiveness, and overall performance in practical applications. In conclusion, the reported error analysis results demonstrate a high level of agreement between the experimental validation data and the simulated data, confirming the effectiveness of the PID controller in regulating the system. However, it's essential to acknowledge the limitations of error analysis and consider additional factors such as noise, disturbances, and modeling inaccuracies that may influence the validation process
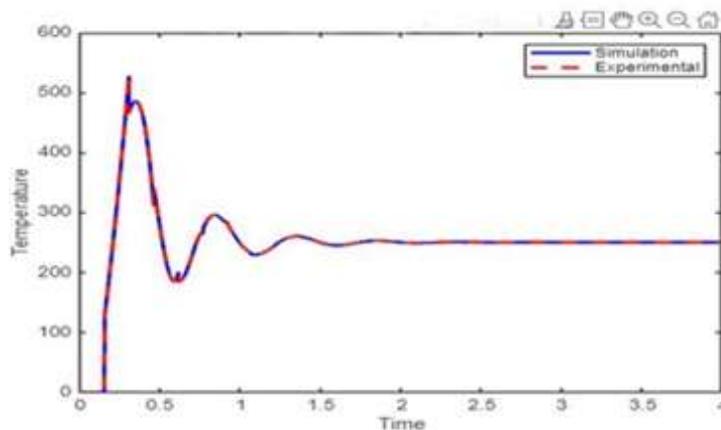

Figure 9. *Validation of Cohen Coon Closed Loop Simulation*

The reported values for Cohen Coon validation, including Integral Absolute Error (IAE), Integral Square Error (ISE), Integral of Time Absolute Error (ITAE), and Integral Time Squared Error (ITSE), provide valuable insights into the effectiveness of the controller tuning technique in real-world applications. A closer examination of these metrics reveals important aspects of the controller's performance and its agreement with experimental validation data. In the context of the provided values IAE: 0.027674, ISE: 0.00041274, ITAE: 0.50774, and ITSE: 0.13437 it is evident that the discrepancies between the experimental and simulated data are minimal, indicating a successful validation process. The low value of IAE suggests that the absolute error between the experimental validation data and the simulated data over the entire time is relatively small. This indicates accurate tracking of the setpoint by the controller, with deviations between the actual and desired values being effectively minimized.

Similarly, the low value of ISE indicates minimal squared error between the datasets, reflecting precise control performance with minimal fluctuations or deviations from the desired trajectory.

Furthermore, the relatively small values of ITAE and ITSE highlight the effectiveness of the Cohen Coon tuning method in minimizing both absolute error and squared error over time. The ITAE metric considers the time-weighted absolute error, where the reported value being relatively low implies efficient tracking of the setpoint throughout the experiment. Similarly, the low ITSE value indicates minimal oscillations or overshoot over time, reflecting stable and robust control performance by the tuned PID controller. The findings from the validation of the Cohen Coon tuning method align with [25], [28], [29], which have emphasized the importance of selecting appropriate tuning techniques to achieve desired control objectives. By demonstrating a high level of agreement between the experimental validation data and the simulated data, the results validate the efficacy of the Cohen Coon method in accurately regulating the system in real-time applications. However, it is essential to acknowledge the potential limitations of the validation process, such as modeling inaccuracies, disturbances, or unaccounted dynamics, which may influence the results. In conclusion, the reported error analysis results for the Cohen Coon tuning method affirm its effectiveness in achieving precise control performance and accurate tracking of setpoints in practical applications. The agreement between the experimental validation data and the simulated data underscores the robustness and reliability of the tuned PID controller, offering confidence in its implementation for real-world control tasks.

Figure 10 gives a plot for the validation of quarter amplitude damping ratio closed loop simulation results below. The reported error analysis results for the Quarter Amplitude Damping Ratio (QADR) tuning method, including Integral Absolute Error (IAE), Integral Square Error (ISE), Integral of Time Absolute Error (ITAE), and Integral Time Squared Error (ITSE), provide valuable insights into the validation of this controller tuning technique. These metrics serve as crucial indicators of the performance of the PID controller in real-world applications, offering insights into its ability to accurately regulate the system dynamics and track desired setpoints.
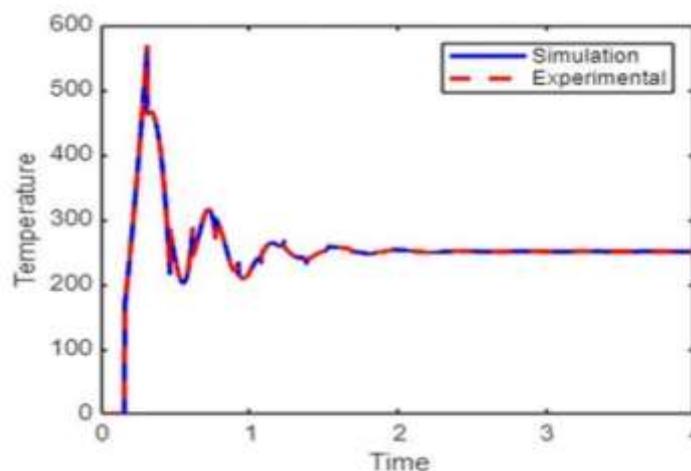

Figure 10. *Validation of QADR Closed loop Simulation*

The obtained values, specifically IAE: 0.14957, ISE: 0.017377, ITAE: 1.0019, and ITSE: 0.42248, shed light on the discrepancies between the experimental validation data and the simulated data. The relatively low values of IAE and ISE suggest that the absolute and squared errors between the experimental and simulated data are relatively small, indicating precise control performance with minimal deviations from the desired trajectory. This implies that the QADR-tuned PID controller effectively minimizes the error between the actual and desired system responses, leading to accurate tracking of setpoints [30]. Furthermore, the values of ITAE and ITSE provide insights into the time-weighted performance of the controller over the entire duration of the experiment. The reported ITAE value of 1.0019 indicates efficient tracking of setpoints over time, with minimal cumulative absolute error. Similarly, the ITSE value of 0.42248 suggests that the controller achieves stable and robust performance, with minimal oscillations or overshoots over time. Comparing these validation results with those obtained for other tuning methods, such as Ziegler Nichols and Cohen Coon, it is essential to consider the relative performance of each technique in terms of error minimization and stability.

While the QADR method demonstrates competitive performance in terms of IAE and ISE, its effectiveness in achieving stable and robust control performance over time, as reflected by ITAE and ITSE, may vary depending on the specific system dynamics and control objectives. In conclusion, the validation results for the QADR tuning method affirm its effectiveness in achieving accurate and stable control performance in real-world applications. By minimizing error metrics and ensuring robustness over time, the QADR-tuned PID controller offers a viable solution for a wide range of control tasks. However, further comparative studies and empirical validations may be necessary to fully evaluate its performance relative to other tuning methods under varying system conditions. The overall table for validation of controller performance error analysis is presented in table 4.

Table 4. *Validation of Controller Performance Error Analysis*

PID Controller Tuning Technique	IAE	ISE	ITAE	ITSE
Ziegler Nichols	0.15102	0.01272	0.20677	0.06193
Cohen Coon	0.027674	0.00041274	0.50774	0.13437
Quarter Amplitude Damping Ratio	0.14957	0.017377	1.0019	0.42248

8. CONCLUSION

In conclusion, this study aimed to develop a PID-based temperature controller suitable for an aluminium extrusion aging furnace and evaluate its performance against existing control methods. Through comprehensive analysis and experimentation, several key findings have been revealed, aligning with the study's specific objectives.

Recommendations and guidelines have been provided for implementing the PID-based temperature control system in aluminum extrusion aging furnaces. These include the adoption of advanced tuning methods such as Ziegler-Nichols and the integration of real-time monitoring and adaptive control strategies to further enhance temperature stability and efficiency. Overall, the study underscores the significance of PID control in optimizing the aluminum aging process, offering insights for enhancing quality, consistency, and energy efficiency in industrial applications.

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