Pyrolysis process control: temperature control design and application for optimum process operation

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ABSTRACT

Fast pyrolysis in auger reactor gains attention for efficient bio-oil production. Due to the quick nature of the process, precise temperature control using the proportional-integral-derivative (PID) algorithm is paramount. This study harnesses various PID tuning approaches through modelling and experimental validation to optimize continuous and precise pyrolysis temperature. System identification was done to investigate the process dynamic with fit accuracy above 93% and design a suitable PID control. Comparison with the experiment data shows a favorable result with rise time and settling time match above 75%. Ziegler-Nichols (ZN) and Cohen-Coon (CC) tuning methods were implemented in the system with undistinguished results, yielding steady-state error (SSE) below 1% and settling time around 4,300 to 4,800 seconds. The heuristic fine-tuning method improved the rise time and settling time by stabilizing before 3,600 seconds. Furthermore, the robustness of PID controllers was verified with a disturbance rejection test, keeping the SSE deviation inside the boundary of 2%. Finally, the setup could support maximum pyrolytic oil production by 69.6% at 500 °C. The result implies that the PID controller could provide a stable and rugged response to support a productive and sustainable pyrolysis plant operation.

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1. INTRODUCTION

In 2010, the global energy consumption was apportioned among different sources, with oil representing 35.3%, coal at 27.0%, natural gas at 20.5%, biomass at 6.3%, nuclear at 5%, hydroelectric at 5.8%, and other renewables at 1.1% [1]. Based on predictions, there will be a considerable increase in the global development and application of sustainable energy solutions, primarily driven by their environmental benefits and the uncertainties associated with an approximate 56% rise in total energy demand [2]. Moreover, forecasts suggest a 20% reduction in oil consumption and a twofold increase in the usage of renewable energy by 2040 [3].

The utilization of renewable sources and repurposing waste materials for energy is on the rise due to many factors, including society's heavy reliance on fossil fuels and growing apprehensions about the impacts of global warming [4]. Climate change and rising energy needs caused by rapid worldwide population increase, urbanization, industrialization, and national development advancements have resulted in massive waste generation, posing a threat to the environment and human health. Furthermore, trash disposal at landfills leads to the release of greenhouse gases. Sustainable waste management strategies contribute to reducing waste generation, optimizing waste reuse and recycling, and mitigating waste's environmental consequences [5]. Moreover, harnessing energy from sustainable sources is a potential solution to minimize climate change impact and the surging global temperature, as recognized by the intergovernmental panel on climate change (IPCC) and international climate change conventions [6].

Thermochemical conversion methods and integrating comprehensive waste management systems are the best solutions for sustainable waste treatment [7]. The utilization of thermochemical conversion methods to transform fossil-based and bio-based waste into alternative liquid fuels can contribute to a future [8]. One of the thermochemical conversion methods is pyrolysis, a thermochemical decomposition process of organic materials conducted without any oxidant, typically at elevated temperatures ranging from 400 °C to 800 °C [9]. The categorization of pyrolysis is divided into slow, fast, or flash depending on the reactor's heating rate and the system's residence time [10], [11].

The fast pyrolysis process has captured the attention of researchers mainly because it has the potential to produce a more significant amount of bio-oil compared to the other two techniques [12]. The primary output of fast pyrolysis in liquid form facilitates its simple storage and transportation. Additionally, a diverse array of reactors is suitable for performing fast pyrolysis. One of them is the auger-type reactor, which stands out for its uncomplicated operation and handling. As a result, the auger reactor is considered one of the most potential reactor configurations for the fast pyrolysis process [13].

Several researchers have explored using the fast pyrolysis process and an auger reactor. Jalalifar *et al.* [14] conducted an experiment that utilized a fast pyrolysis process in a pilot-scale auger reactor modelled through computational fluid dynamic (CFD) simulation. The optimal temperature for maximizing the bio-oil yield was 500 °C for the specific feedstock and reactor. Moreover, higher feed flow rates within the studied range of biomass feed flow rates (1–4 kg/h) led to increased bio-oil yield. Huo *et al.* [15] carried out experiments to explore the liquid product yields from the catalytic pyrolysis of low-density polyethylene (LDPE), resulting in yields of 60.9 wt% (450 °C), 72 wt% (500 °C), and 68.5 wt% (600 °C).

Precise temperature measurement and control are pivotal in numerous industrial and scientific processes. However, achieving rapid and accurate temperature changes with high stability becomes challenging when intricate thermal interactions arise among the heat source, controlled mass, and heat sink within traditional heater-controlled systems [16]. The controller's accuracy and sensitivity influence the precision of temperature regulation in a heater [17], [18]. Hasan *et al.* [13] stated in their research that different temperatures can lead to a 10%–20% difference in the bio-oil yield. Elevating the pyrolysis temperature leads to volatile cracking processes, resulting in a decline in bio-oil yield and increased gas generation. Conversely, lowering the temperature promotes the production of significant amounts of biochar.

According to Greco *et al.* [19] a dependable temperature controller is crucial to ensure temperature stability when the pyrolysis reactor is in continuous operation. Despite the emergence of new controller algorithm candidates, such as model predictive control (MPC), proportional-integral-derivative (PID)-fuzzy, and neural network-based methods like reinforcement learning (RL), proportional-integral-derivative (PID) controller supremacy remains undisputed due to its reliability, versatility over various process application and operating condition, easily obtained hardware, well-known by engineers and operators, coupled with its ability to maintain stability despite disturbance and fast response [20]–[22]. Furthermore, a survey conducted by Samad *et al.* [23] revealed that PID control still had a current impact of 91% and will maintain the impact in the next five years by 78%. To date, PID controllers have seen countless successful implementations with various tuning methods, such as modified grey wolf optimization (mGWO) for liquid level control [24], improved Marine predators algorithm tuned with additional fractional-order tuning parameter for automatic voltage regulator (AVR) system [25], and back propagation neural network (BPNN) for a motion control system embedded in a field programmable gate array (FPGA) [26]. Its adaptability extends to linear and nonlinear systems, irrespective of their response speed [20]. The standard approaches for tuning PID controllers are Ziegler-Nichols (ZN), relay method, Cohen-Coon (CC), and Chien-Hrones-Reswick methods [27]–[30].

The goal of this research is to design and implement a robust and stable PID control system that supports pyrolysis plant operation through a combination of simulation and experimental methods. Simulation is done by creating the plant mathematical model to design the PID controller by system identification method taken from the pseudo-random binary sequence (PRBS) technique. The outcome was then contrasted with the actual experiment data to determine the match percentage. Three tuning methods will be implemented, namely Ziegler-Nichols (ZN), Cohen-Coon (CC), and an improved, heuristic-based Cohen-Coon (CC) called fine-tuning method at a setpoint of 500 °C. Then, PID controller robustness was examined through a disturbance rejection test by feeding the reactor with 500 g/hr of tyre waste. Finally, the fine-tuning PID will be implemented during the pyrolysis plant operation, with the product yield being observed. The controller's responses were then analyzed and discussed.

Although PID control implementation by using the ZN and CC methods might seem old-fashioned, this investigation provides novel insights into the design and application of PID control for optimizing pyrolysis process operations, addressing the specific challenges posed by the continuous nature of the process and the unique characteristics of the auger reactor. Furthermore, a holistic comparison between the simulated system and in-situ application was made and assessed.

2. METHOD

2.1. System architecture

The system architecture for pyrolysis temperature control using PID control comprises data acquisition (DAQ) modules from national instruments (NI) connected to a computer via a universal serial bus (USB), thermocouple, mass flowmeter, electric heater and a motor. The DAQ system consists of a mainframe, in this case, the NI-DAQ 9178, which acts as a hub for the individual DAQ modules. The NI-DAQ 9178 is connected to the computer via USB, allowing for real-time data acquisition and processing. The system architecture also includes three individual DAQ modules: the NI 9211, the NI 9201, and the NI 9474. Figure 1 depicts the pyrolysis control and monitoring system architecture.

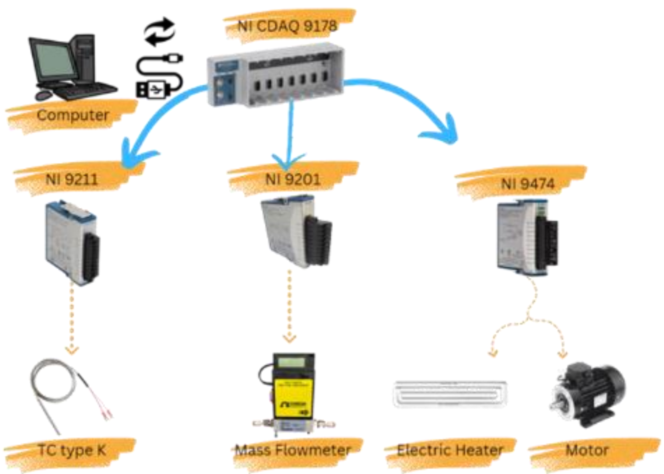

Figure 1. Control system architecture of pyrolysis process

2.2. PID control system

The three components of PID control can be combined to create a controller capable of responding to a wide range of system disturbances and setpoint changes. The specific proportional gain (K_p), integral time (T_i), and derivative time (T_d) values are typically tuned through trial-and-error or advanced optimization techniques to achieve the desired system performance. The block diagram of the PID controller is depicted in Figure 2, wherein *R(s)* represents the setpoint, *e(t)* denotes the error, *P(s)* signifies the plant model and *Y(s)* corresponds to the output.

First, the transfer functions of the pyrolysis process will be deduced via a data-driven approach. Then, this transfer function is subsequently harnessed in simulating the PID controller's behavior, enabling the derivation of transient responses. The response from the PID simulation will be validated by integrating the PID parameters into the actual pyrolysis setup, thus affirming the authenticity of the simulation results.

The validated PID transient responses were then juxtaposed with the outcomes achieved through classical tuning methodologies, specifically the ZN and CC tuning methods, with the parameters obtained based on the open-loop response. Drawing from system dynamics, these approaches entail using experimental methods or dynamic plant simulations to create step-response curves. This holistic analysis showcases the integration of theoretical and practical aspects, crucial in comprehending pyrolysis process control dynamics.

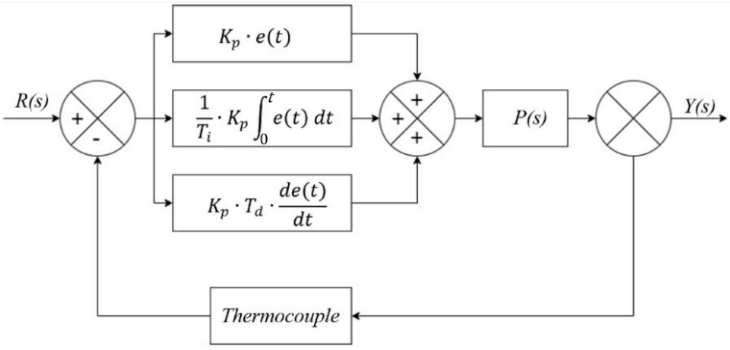

Figure 2. Proportional-integral-derivative (PID) controller block diagram

These S-shaped curves are described by two constants known as the delay time (L) and time constant (T). A tangent line is drawn by the inflexion point of the S-shaped curve to determine these values. The variables, such as the percent change of input (P), the percent change of output (N), dead time (L) and time (R), will be used as input for ZN [31] and CC tuning rules [32] as described in Figure 3 and Table 1.

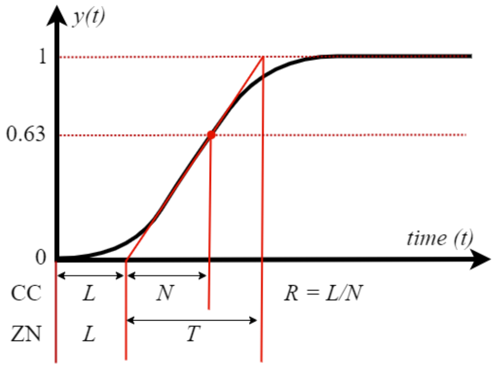

Figure 3. S-curve for ZN and CC tuning methods

Table 1. Ziegler-Nichols (ZN) and Cohen-Coon (CC) PID tuning rule

PID tuning method	K_p	T_i	T_d
ZN	$1.2\frac{T}{L}$	2L	0.5L
CC	$\left(\frac{P}{NL}\right)\left(1.33+\left(\frac{R}{4}\right)\right)$	$L\left(\frac{30+3R}{9+20R}\right)$	$\frac{4L}{(11+2R)}$

The system requirements for the pyrolysis temperature control can be seen in Table 2. The setpoint is set at 500 °C, with a maximum allowable overshoot of 2% to minimize temperature deviation and avoid a decline in the bio-oil product [13]. As indicated by the rise time requirement of ≤3,000 seconds, a fast response is required to minimize the time to reach the setpoint. The steady-state error must be kept under 2% by the control system's basic rule [31]. Moreover, the settling time should also be ≤3,600 seconds to maintain temperature stability within an acceptable range around the setpoint.

Table 2. Control system design requirement

Requirement	Value
Setpoint	500 °C
Maximum overshoot	2%
Rise time	≤3,000 s
Steady-state error	≤2%
Settling time	≤3,600 s

2.3. Controller design

The PID control algorithm deployed in the LabVIEW software for the pyrolysis process's temperature control using thermocouple feedback. The PID controller determined actuator output based on feedback and maintained the desired temperature by controlling solid-state relays (SSRs) that managed energy supplied to electric heaters. The control signal from the PID controller regulated the 1,200 W heater via a NI 9474 module. This will enable precise control of the SSR, known for its reliability and fast switching. The NI 9474 module translated the PID controller's signal into a digital one, accurately modulating heater power. Figure 4 depicts the hardware setup, including the NI-DAQ 9178 data acquisition system (1), SSR heater (2), and electric heater connections (3), highlighted in red.

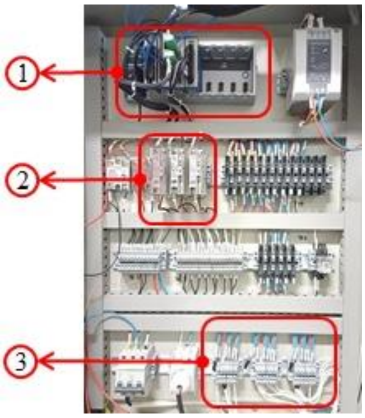

Figure 4. Hardware controller design

2.4. Experiment setup

Figure 5 displays the auger reactor configuration. There are three control loops in the pyrolysis reactor, specifically T3 (preheating section), T4 (first part of reactor) and T5 (second part of reactor). Five type-K thermocouples are installed along the auger reactor as feedback sensors. These thermocouples are equipped with electric heaters with 1,000 watts each to control the temperature throughout the pyrolysis reaction area by using the temperature data from these feedback sensors. This closed-loop control system ensures precise and consistent temperature regulation, optimizing pyrolysis for efficient waste conversion.

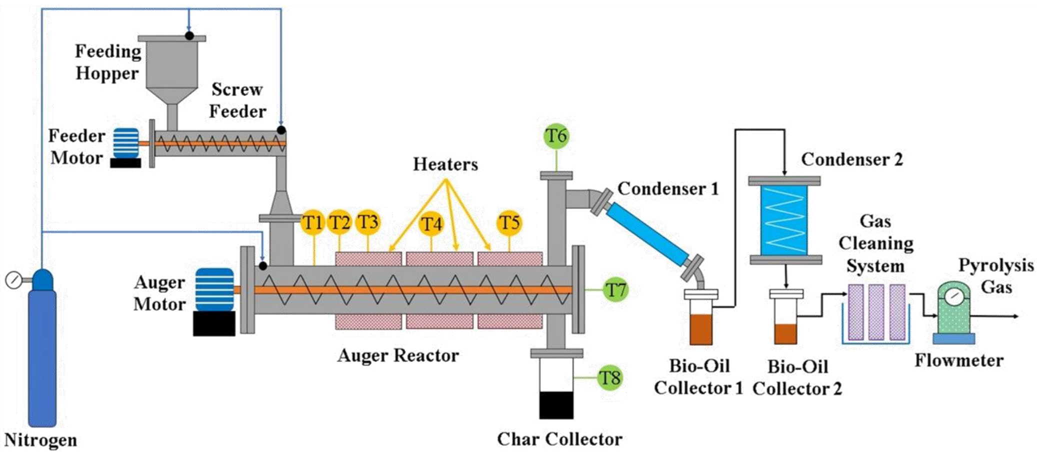

Figure 5. Auger reactor experiment setup for the pyrolysis process

3. RESULTS AND DISCUSSION

3.1. Control system design simulation

Utilizing the system identification Toolbox in MATLAB played a pivotal role in the control design. Its primary functions encompass the comprehensive analysis of a system's characteristics, enabling users to gain profound insights into its dynamic behavior and inherent properties. Furthermore, it facilitates the creation of precise mathematical models based on real-time measurements and experimental data, a crucial step in designing effective control strategies for optimizing and regulating the system's behavior [33].

3.1.1. Transfer function plant identification for PID simulation

There are three main steps in getting the transfer function of the system model. First, data acquisition consists of open-loop input and output data [34]. A total of 7,150 data points were taken for each control loop, with the input from the SSR ranging from 0 to 100% that triggered the heating command in the reactor and the output is the measured reactor temperature. A PRBS signal was chosen to generate the output response due to its simplicity for iterative signal generation and producing the desired result, triggering the output continuously [35]. Figure 6 depicts the input and output of the open loop system using the system identification toolbox in MATLAB.

After data acquisition, the second step is model estimation using the system identification toolbox in MATLAB. The estimation process is done to obtain the highest fit percentage. Continuous transfer functions for each loop were identified utilizing the transfer function identification (TFEST) command with no zeros, two poles and three free coefficients. Table 3 displays the result with over 90% fit estimation data for T3, T4, and T5.

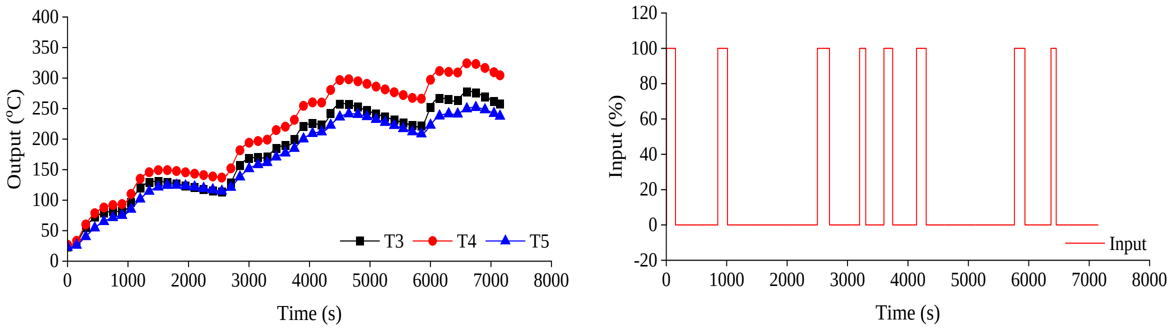

Figure 6. Input and output signal

Table 3. Identification of transfer function

	Transfer function	Fit estimation data
T3	$\frac{1.861e-05}{s^2 + 0.005205s + 8.138e-07}$	93.88%
T4	$\frac{1.737e-05}{s^2 + 0.004285s + 6.179e-07}$	94.40%
T5	$\frac{1.052e-05}{s^2 + 0.002795s + 5.75e-07}$	93.71%

3.1.2. PID simulation transient response

There are four main classifications of damping ratio (ζ) in control engineering design. First, undamped ($\zeta = 0$) with no damping in the system and sustained oscillation. Second, underdamped ($0 < \zeta < 1$), with fast rise time and overshoot in the response. Third, critically damped ($\zeta = 1$) with slower rise time compared to underdamped and minimum overshoot. Finally, overdamped ($\zeta > 1$), with the slowest rise time among all. Figure 7 shows the response comparison between different values of the damping ratio.

For the pyrolysis temperature control design, the simulation will start with a critically damped system with $\zeta = 1$. After achieving a critically damped ratio, the PID parameters will be subsequently tuned to meet the design requirements, as indicated in Table 2. Figure 8 shows the transient response from the simulation result, and Table 4 displays the detailed specification parameter.

The system simulation response for the rise time, settling time, and steady-state error showed that the selected values for K_p, T_i, and T_d have met the minimum requirement described in Table 2. The settling times, achieved when the steady-state error is less than 2%, are 2,300 seconds, 2,650 seconds, and 2,760 seconds, respectively, for T3 to T5. However, the maximum overshoot for T3, T4, and T5 exceeds the minimum requirement, with values of 6.42%, 9.84%, and 9.42%, respectively. Hence, ZN and CC tuning methods will be used to reduce the overshoot.

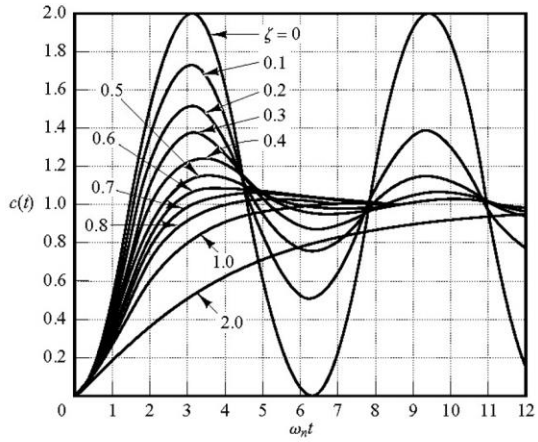

Figure 7. Response comparison of damping ratio [31]

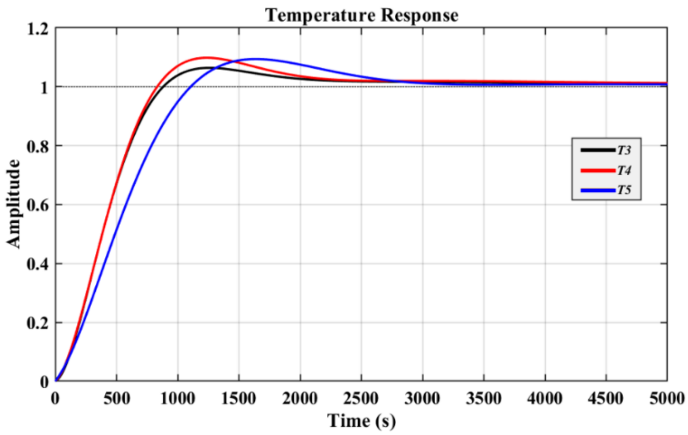

Figure 8. PID simulation result

Table 4. Specification parameter of the PID simulation

	K_p	T_i (s)	T_d (s)	Max overshoot (%)	Rise time (s)	Settling time (s)	Steady state error (%)
T3	0.70	100	10	6.42	588	2300	< 2
T4	0.65	100	20	9.84	577	2650	< 2
T5	0.55	110	50	9.42	787	2760	< 2

3.2. Comparison between simulation and experiment response

The simulation-based tuning method yielded transient response values that substantially diverged from the experimental results. Notably, the overshoot values were considerably high for scenarios T4 and T5, reaching 15.98% and 16.21%, respectively. This significant discrepancy indicates that the simulation might not fully capture the intricacies of the actual pyrolysis process, underlining the challenge of accurately modelling its dynamic behavior [36]. The rise times were relatively rapid, ranging from 438 to 545 seconds, showing the potential for quick control responses. However, the elevated overshoots underscore the limitations of relying solely on simulation for parameter tuning.

The transient response results obtained from simulation and implementation for T3, T4, and T5 of the pyrolysis temperature control exhibit varying degrees of similarity and deviation. Table 5 shows the percentage of match simulation and implementation data. T3 demonstrates a relatively good match in rise time and settling time between simulation and implementation (86.23% and 92.46%, respectively), while the overshoot notably deviates (10.46% compared to 6.42% in simulation). In T4, the rise time and settling time exhibit better correspondence (75.93% and 75.09%, respectively), yet the overshoot differs significantly (15.98% compared to 9.84% in simulation). T5 shows a reasonable fit in rise time (30.78%) but deviates notably in overshoot and settling time (16.21% and 3,226 seconds compared to 9.42% and 2,760 seconds in simulation). Overshoot of overall sections shows the lowest match compared to another transient parameter, with less than 40%. The actual overshoot of the system is barely reduced due to the system having no cooling. The system with no cooling and only depends on the natural effect is slow in reducing temperature [37].

Table 5. Percentage of match simulation and implementation data

	Max overshoot match (%)	Rise time match (%)	Settling time match (%)
T3	37.02	86.23	92.46
T4	37.90	75.93	75.09
T5	28.35	69.22	85.46

The experimental tuning phase involved conducting an open-loop experiment to obtain the S curve of the system. By observing the system's response without any feedback control, the inherent dynamics and characteristics of the system were identified. Subsequently, the ZN and CC tuning rules were implemented based on the obtained S curve as described in [31], [32], [36] . These tuning methods allowed for determining appropriate PID controller parameters, including the proportional, integral, and derivative gains, to achieve the desired control performance. The experimental tuning process enabled a systematic approach to optimize the control strategy for the specific pyrolysis process, ensuring accurate and stable temperature control.

Figure 9 shows the PID controller's response to various tuning methods, with the result of simulation validation in Figure 9(a) seen with overshoot, the real-time implementation of ZN, CC method in Figures 9(b) and 9(c), and the improvement done by empirical fine-tuning method in Figure 9(d). ZN and CC tuning methods exhibit competitive transient responses in overshoot, rise time, settling time, and steady-state error. Both methods managed to maintain values below 0.317% for overshoot, indicating their effectiveness in controlling temperature deviations. On the other hand, the rise time obtained with CC tuning is notably shorter than the ZN tuning's range of 400 seconds. A shorter rise time is highly beneficial in dynamic systems like pyrolysis, where precise temperature control is crucial for optimal product yield and energy efficiency [19]. It enhances the process's responsiveness to external factors, such as variations in feedstock composition or heating conditions, which can directly impact the product quality and process efficiency. Therefore, the superiority of CC tuning in achieving shorter rise times underscores its potential to provide more agile and accurate control in the pyrolysis temperature control process.

PID parameter and transient response can be seen in Table 6. Comparing the settling time achieved through the ZN and CC tuning methods, it is evident that both methods yield relatively similar results. The settling time for CC ranges from 4,380 to 4,880 seconds, while those for ZN range from 4,443 to 4,750 seconds. These values indicate that both methods provide adequate control performance regarding how quickly the system maintained a steady-state condition. Notably, both methods achieved steady-state errors well below 1%, highlighting their competence in process regulation vigilance.

Among these methods, the CC tuning method is the most suitable for precise pyrolysis temperature control due to its effective balance between performance and stability. However, its settling time might fall short of the minimum requirement. Therefore, a heuristic adjustment based on the CC tuning method is needed to achieve the desired results, which is called fine-tuning [36], [38]. This will act as a crucial refinement step that bridges theoretical predictions with practical implementation, enabling optimization tailored to the pyrolysis process dynamics.

The fine-tuning method meticulously addresses the intricacies of the specific system dynamics through iterative parameter adjustment. The interplay between K_p, T_i, and T_d in a PID control system profoundly shapes the control response for dynamic processes [36]. The PID parameter spectrum spans from initial simulation-based values to those derived from ZN and CC methods.

Given that T_d values from the CC method are well-suited for reducing overshoot and anticipating future errors, the primary modification focus is on Kp and T_i. The challenge in pyrolysis temperature control lies in balancing K_p and T_i to achieve rapid temperature adjustments without overshooting. A high K_p coupled with a small T_i accelerates response but can destabilize, while a small K_p with a large T_i stabilizes at the cost of slower convergence. Therefore, the objective is to find the equilibrium between K_p and T_i that ensures a swift response, stability, and minimal deviation in temperature control, which is crucial for efficient pyrolysis.

The procedure of fine-tuning method is as follows. First, the PID parameters of the CC method were initialized to the system, and the T_d parameter was kept constant. Second, the K_p parameter was decreased by around half to a quarter of the initial value, and the T_i parameter was adjusted. Finally, the pyrolysis plant was restarted again to check the settling time requirement. If the requirement is not fulfilled, then the K_p and T_i parameters are readjusted again.

Fine-tuning achieves the desired results by minimizing overshoot to 0.45%, 0.60%, and 0.71% for T3, T4, and T5, respectively, as shown in Figure 9(d). It ensures efficient temperature control and steady-state errors maintained below 1%. Moreover, the fine-tuning response showcases suitable transient response dynamics for pyrolysis, improving accuracy and stability. The combined reduction in overshoots, increase in rise time, and steady-state errors underline the method's aptitude for enhancing the plant's overall control performance.

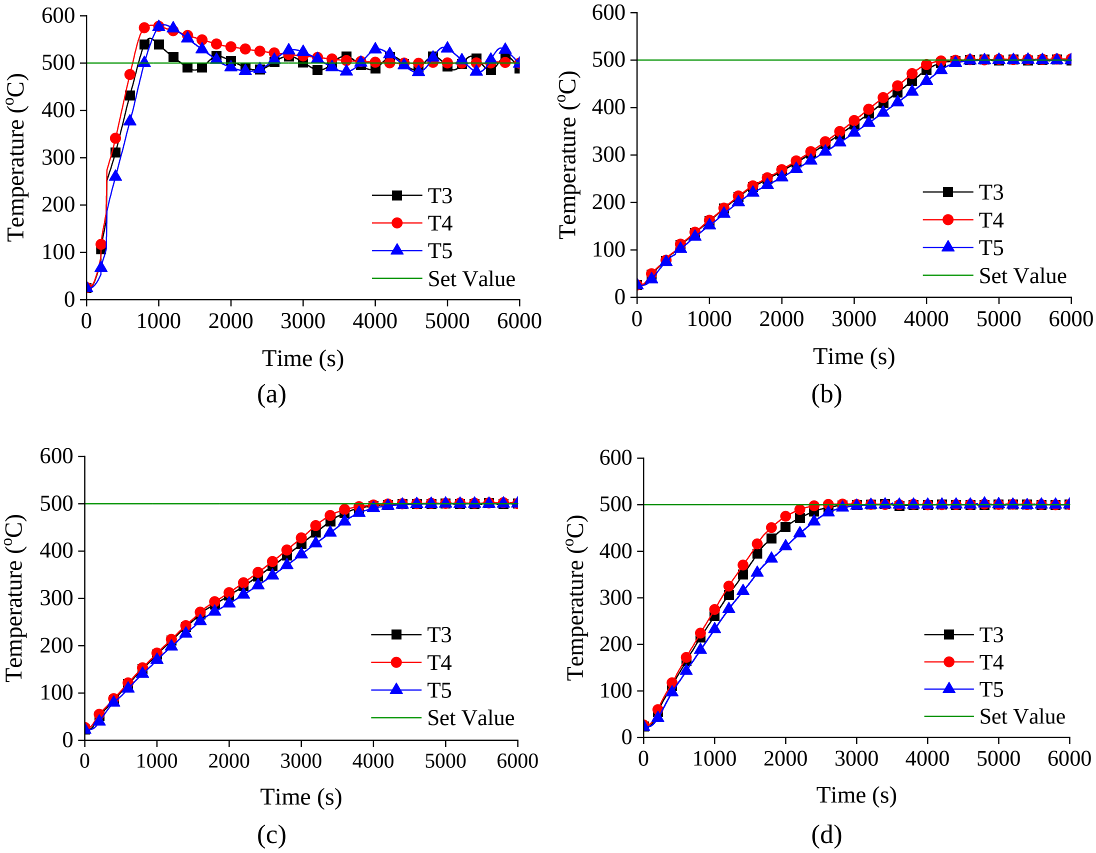

Figure 9. PID controller response of (a) tuning simulation validation, (b) ZN method, (c) CC method, and (d) fine-tuning method

Table 6. PID parameter and transient response

	Tuning method	K_p	T_i (s)	T_d (s)	Max overshoot (%)	Rise time (s)	Settling time (s)	Steady state error (%)
T3	Simulation	0.70	100	10	10.46	507	2474	> 2
T4		0.65	100	20	15.98	438	3310	< 2
T5		0.55	110	50	16.21	545	3226	> 2
T3	ZN	7.76	412	103	0.30	3537	4500	< 1
T4		8.54	366	92	0.31	3431	4443	< 1
T5		7.16	434	109	0.05	3681	4750	< 1
T3	CC	8.85	519	162	0.30	3096	4380	< 1
T4		13.89	974	129	0.31	2993	4380	< 1
T5		7.16	1152	156	0.05	3249	4880	< 1
T3	Fine-tuning	2.52	666	162	0.45	1794	3008	< 1
T4		3.28	526	129	0.60	1662	2605	< 1
T5		3.25	615	156	0.71	2055	3208	< 1

3.3. Disturbance rejection system test

A 500 g/hr tyre waste was introduced to the reactor operating with a constant speed of 200 rpm to examine PID controller robustness. The resulting response in Figure 10 highlights the oscillation range for different scenarios. Notably, in the case of T3, the oscillation range reaches a maximum of 2%, while for T4 and T5 is less than 1%.

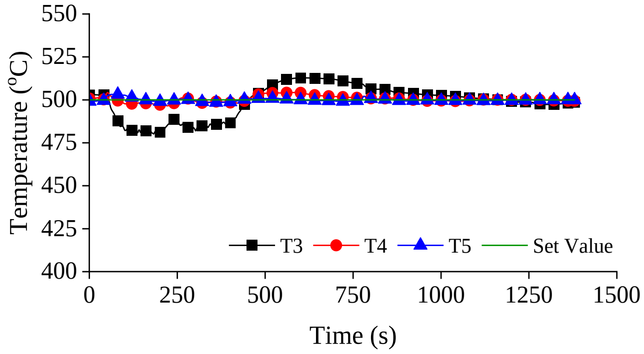

Figure 10. Disturbance rejection test result

The positioning of T3 causes a discrepancy in oscillation ranges as it is the first contact point with the waste. This initial point of contact exposed T3 to the fresh tyre waste material, leading to higher disturbances and relatively frequent oscillation due to the heat transfer. Moreover, the speed at which T3 reaches its setpoint of stability, approximately 500 seconds, emphasizes its sensitivity to disturbances.

This observation resonates with the fine-tuning results, where the fine-tuning approach significantly reduced overshoots and steady-state errors. The fine-tuning parameters align the system's response more closely with the desired setpoints, thus dampening the oscillations caused by external disturbances. The other two sections (T4 and T5) also play crucial roles. The dampened oscillation in T3, T4, and T5 showcases the effectiveness of fine-tuning in achieving stable control across all sections of the pyrolysis reactor.

3.4. Production result

The pyrolysis plant was operated with fine-tuning PID set-up, tyre waste feed of 13.33 g/min, and various setpoints ranging from 400 °C to 600 °C. The result is then recorded in Table 7. It was observed that the highest oil yield was reached at the 500 °C setpoint, with 69.6 wt%, corresponding with the studies in [8], [15], and [39]. Therefore, the fine-tuning PID setup was able to support maximum pyrolytic oil production by maintaining the plant’s temperature at 500 °C.

Table 7. Pyrolysis plant product yield

Setpoint (°C)	Oil (liquid) yield (wt%)	Solid (char) yield (wt%)	Non-condensable gas (wt%)
400	52.2	43.99	3.81
500	69.6	23.82	6.58
600	63	25.77	11.23

4. CONCLUSION

Robust and stable PID controllers were designed and implemented successfully for every control loop in the pyrolysis reactor. The system identification method was employed to determine the transfer function from the data excited by the PRBS signal, with the fit estimation data of 93.88%, 94.40% and 93.71% for T3, T4 and T5, respectively. PID controllers for simulation purposes were created with minimum overshoot, error steady state below 2%, and settling time of less than 3,000 seconds for each control loop, fulfilling the system’s requirement. Although the PID controllers' simulation result and field implementation had a considerable difference below 40% for the overshoot condition, it shows an agreeable similarity in rise and settling time ranging from 69.22% to 92.46% for T3 to T5.

The applied PID controllers were tuned under ZN and CC. Both have an identical response with steady-state error and a maximum overshoot of less than 1%. However, the settling time is outside the requirement. Therefore, an intuitively improved CC method (fine-tuning) is deployed to fasten the settling time to 3,008, 2,605, and 3,208 seconds for T3, T4 and T5 at the expense of negligible overshoot. The disturbance rejection test showed that PID controllers could maintain the reactor temperatures inside error steady-state criteria of 2% for T3 and 1% for T4 and T5 despite feed input. Moreover, the tuning implementation into the pyrolysis plant could support pyrolytic production impeccably by 69.6 wt% at 500 °C.

This investigation offers another insight into the proposed self-tuning CC method that fastens the response’s settling time and reinforces pyrolytic oil optimal production. On the other hand, the similarity between the transfer function estimation and the experiment result is justified by the rise and settling time match. The present study lays the groundwork for future research in performing other methods such as MPC, RL, and PID-fuzzy to develop the controller to minimize control input or simplify the tuning process.

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