

RESEARCH ARTICLE

PID control mechanism for the impact of pyrolysis temperature on bio-oil yield from biomass feedstock

A.H.S. Ahmad Tabrani¹, N.H. Kasmuri^{1,2*}, F. Subari^{1,2}, Z. Abdullah¹, S.H. Hanipah¹¹ Faculty of Chemical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia² Surface Coating Group, Faculty of Chemical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

Abstract - The global population is expected to increase on a yearly basis. To meet the energy demands of this rapid expansion, researchers must identify new alternative energy sources and replace depleted fossil fuels with other sources, such as biomass. Biomass can be thermochemically converted into bio-oil through pyrolysis; however, the conventional pyrolysis method lacks adequate process control. This study aims to analyze the effects of temperature on the effectiveness of disturbance in pyrolysis. The temperature was adjusted to determine the bio-oil yield as the primary process variable. MATLAB was employed to simulate data from the preceding case study using the Proportional Integral Derivative (PID) controller method. Transfer functions were developed during system identification to assess the efficiency of the order systems adopted. The PID controller was also used to evaluate the impact of disturbances on the process control system. The experiment was divided into four groups: PID controller with 0 zeros, 0 zeros with disturbance, 1 zero, and 1 zero with disturbance. Various transfer functions were applied to convert each group into first-, second-, and third-order systems. The results indicated that the first-order system produced the most stable process and met the target yield of 72%. This dataset can be used to advance current research on bio-oil yield optimization using the PID control mechanism as a component of the process control system.

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1. Introduction

Fossil fuel consumption has increased rapidly, depleting energy resources and significantly impacting climate change [1]-[3]. Biomass feedstock has the greatest potential to replace fossil fuels as a new energy source. The difference between fossil fuels and biomass lies in their advantages as clean energy sources. Despite extensive research demonstrating the benefits of biomass, e.g., its renewability and lower carbon emissions compared to fossil fuels, its full potential is not yet widely accepted due to limited public awareness. The products obtained from biomass include bio-oil, bio-char, and syngas. Specifically, bio-oil yield can be improved through pyrolysis [4]-[5]. The modes of pyrolysis can be categorised as fast, slow, or vacuum pyrolysis. Based on previous research, fast pyrolysis can achieve the highest bio-oil yields [6]. Therefore, the proposed research focused on fast pyrolysis and introduced a disturbance process to evaluate its effectiveness. In this study, the manipulated input for the primary process was temperature, which was controlled to influence the pyrolysis reaction. The process output was the bio-oil yield, which represents the primary product of interest. The effect of disturbances on the process was explored by using the biomass feed rate as the disturbance input and the bio-oil yield as the output. The experiment classified the variables into three categories: (i) manipulated inputs, such as variations in temperature for controlling the process; (ii) process variables, which mainly included bio-oil yield for measuring process performance; and (iii) disturbances, where variations in biomass feed rate were used to measure system response. Through the identified input-output relationships, transfer functions were modelled using MATLAB's System Identification Toolbox. This enabled analysis of the system's different orders and zeros, as well as the effects of manipulated inputs and disturbances on bio-oil yield.

There is a gap in the use of process control systems in pyrolysis. Therefore, there is a deficiency in the current use of process control systems in biomass pyrolysis, particularly in maintaining steady temperatures and product yields due to the highly non-linear and disturbance-prone nature of the process [7]. It is essential to meet the demands of the industrial revolution to progress towards Industry 4.0, which results in intelligent machines capable of assessing and diagnosing problems without human input. MATLAB can implement a Proportional-Integral-Derivative (PID) control technique. The main emphasis is on the PID controller because of its ability to regulate temperature and achieve accurate product yields. In addition, a reliable PID controller should be employed to ensure temperature stabilisation during the operation of the pyrolysis reactor [8]-[9]. It is relatively easy to design a PID controller, inexpensive to apply, and minimises human errors [10]. The process of thermochemical biomass pyrolysis is characterised by heat sensitivity, intervariable relationships, and nonlinearity. Product distribution and stability are influenced by factors such as temperature, heating speed, residence time, and feeding speed. The key to control involves accurate sensing, modelling, and regulation [11]. Conventional proportional-integral-derivative controllers are still widely employed for temperature regulation in pyrolysis reactors and demonstrate high stability and disturbance rejection, especially for optimal bio-oil production. PID controllers optimise the heating process and reduce activation energy, which improves temperature monitoring, response time, and energy efficiency in biomass pyrolysis [12]. In developing a PID control mechanism in MATLAB for setting

the bio-oil yield set point, the primary goal of this study is to assess how temperature affects pyrolysis. This simulation focused on the impact of disturbances on the PID control mechanism's process behaviour. The second goal of this study is to compare the outcomes of the PID control mechanism simulation run in MATLAB with alternative order systems.

2. Materials and Methods

2.1 Parameters Data

2.1.1 Input and Output Data

The experiment was conducted using a simulation study. In the Simulink interface, the complete PID control system was built to run the simulation. The transfer function was generated using the System Identification Toolbox, which requires input and output data. The parameters indicated in Table 1 designate temperature as the input, bio-oil yield as the output, and biomass feed rate as the disturbance, derived from the previous case study. In a detailed explanation, the total number of runs shown in Table 1 represents 30 data points. For selecting 0 and 1 zeros without disturbance, the temperature input was selected, and the bio-oil yield was designated as the output in the system identification. This data selection was performed to obtain the process transfer function before proceeding to the subsequent simulation. For 0 and 1 zeros with disturbance, the input data selection was modified, with biomass feed rate designated as the input and bio-oil yield as the output. The objective was to simulate the new transfer function in the presence of disturbance and compare the conditions with and without disturbance during pyrolysis.

Table 1. Input and output data [16]

Run	Temperature (°C)	Bio-oil Yield (wt.%)	Biomass Feed Rate (kg/h)	Run	Temperature (°C)	Bio-oil Yield (wt.%)	Biomass Feed Rate (kg/h)
1	450	66.7	3	16	550	69.7	3
2	500	67.3	2	17	550	69.8	3
3	500	67.8	2	18	550	70.1	3
4	500	67.4	4	19	550	71.1	3
5	500	69.3	4	20	550	69.2	5
6	500	66.1	2	21	550	67.2	3
7	500	67.1	2	22	600	68.3	2
8	500	65.7	4	23	600	70.4	2
9	500	68.0	4	24	600	69.1	4
10	550	69.7	3	25	600	72.0	4
11	550	70.4	1	26	600	68.4	2
12	550	69.0	3	27	600	69.1	2
13	550	70.2	3	28	600	69.0	4
14	550	68.9	3	29	600	70.7	4
15	550	68.2	3	30	600	64.4	3

2.1.2 Generating the Transfer Functions

Transfer function modelling has increasingly been used to model the dynamical behaviour of the biomass pyrolysis process, particularly its dependence on changes in feed rate and temperature. Biomass pyrolysis is essentially a nonlinear process that depends on temperature to achieve optimal results [13]-[14]. Temperature affects not only the amount but also the product yield from the biomass. On the other hand, linearization via transfer functions has been successfully achieved and can be used to develop effective process controls. Transfer functions provide a system description using the model's poles and zeros, which dictate the system's response time, stability, and susceptibility to disturbances [15]. The identification of systems using computational methods with software packages such as the MATLAB System Identification Toolbox yields accurate models for controller design in thermochemical processes. Such models facilitate improved process stability and maximise energy utilisation while minimising feed flow variations during pyrolysis. Data collected from the previous case study were classified into three groups, namely manipulated variables (temperature), process variables (bio-oil yield), and disturbances (biomass feed rate), and then stored in the MATLAB workspace [16]. The System Identification Toolbox was used to create transfer function models of the biomass pyrolysis process using input and output data gathered through measurements. In the main process, temperature is considered as the input, while bio-oil yield is the output. Transfer functions with 0 and 1 zeros were created to model the system dynamics, where a zero of 0 denotes a constant numerator, while a zero of 1 denotes a first-order numerator effect. The denominator order determines the poles of the system, while first-, second-, and third-order systems were simulated to examine the dynamics of the system. This was done in MATLAB by defining the transfer function with the obtained numerator and denominator coefficients and employing linear simulation techniques for the given input data.

In disturbance modelling, biomass feed rate was treated as an input variable, whereas bio-oil yield was treated as an output variable. Different transfer functions were developed based on the number of zeros, specifically 0 and 1 zeros, to model the impact of disturbances on bio-oil yield due to biomass feed rate changes. For the 0-zero transfer function, the biomass feed rate was directly input into the transfer function that had a constant numerator, such that only the poles of

the transfer function influenced the output dynamics. On the other hand, the 1-zero transfer function introduces a single zero that influences the output dynamics. The simulation process in MATLAB involved importing workspace data, developing transfer functions, and generating output variables. This technique gave a systematic approach for studying the impact of manipulated variables and disturbance on bio-oil yield.

2.2 Process Simulation Development

The Simulink model details the process of the closed-loop system. Here, the transfer function block represents the value from the transfer function in the system identification process. The simulation began with a termination time of 400 s, and the "Run" button was selected. The result was found to reach the set point in a new window, producing a stable process response.

2.2.1 Tuning the PID Controller

The process simulation was tuned using the PID Tuner toolbox until it achieved its setpoint and presented a stable process response. The tuned response generated new values for the proportional, integral, and derivative components. The complete process simulation involved the PID controller value obtained in the MATLAB Simulink toolbox. Figure 1 presents the complete simulation process for 0 zero, which consists of the first order, second order, and third order. The simulation was repeated using a PID controller for 0 zeros with disturbance, 1 zero, and 1 zero with disturbance.

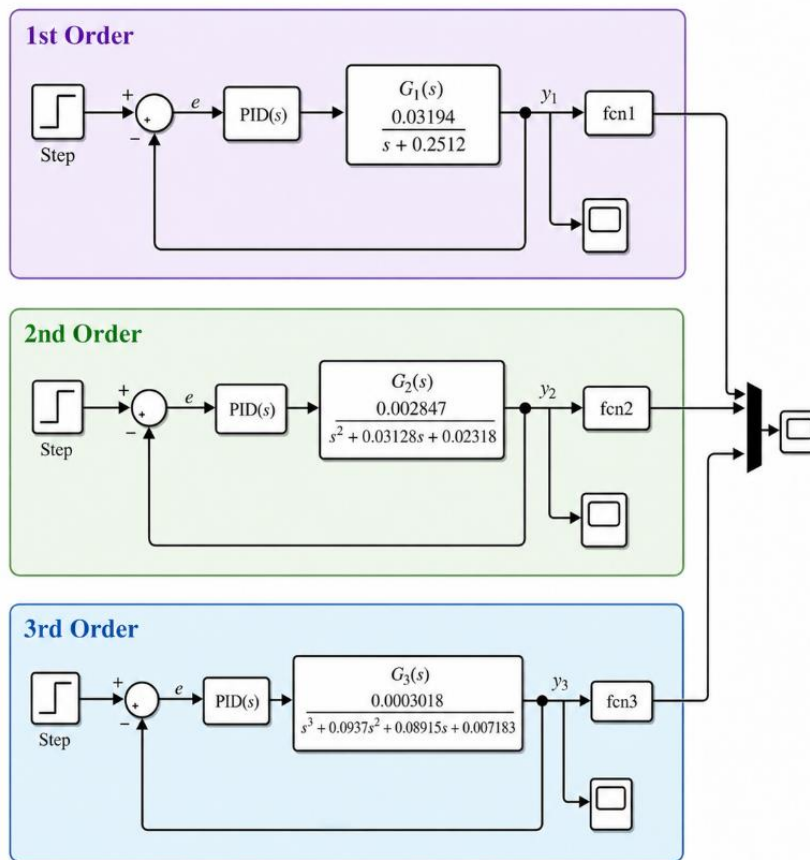


Figure 1. PID controller simulation for 0 zero using MATLAB in (a) first-, (b) second-, and (c) third-order systems

3. Results and Discussion

3.1 PID Controller

The PID control mechanism was examined using four groups: 0 zero, 0 zero with disturbance, 1 zero, and 1 zero with disturbance. In each group type, the time response of the order system was divided into three categories: first-order, second-order, and third-order. This is to ensure the best result for the constructed transfer function. The first-, second-, and third-order transfer functions were derived using system identification techniques, based on the experimental input-output data obtained from the pyrolysis process. The gain was determined from the steady-state output, with a target of 72% bio-oil yield. The time constants were extracted from transient characteristics, such as rise time, settling time, and percentage response, which fell outside the research scope. Higher-order systems required approximation using dominant dynamics, as multiple poles influenced the response shape.

3.1.1 PID Controller for 0 zero

Figure 2 compares the order system at zero. Figure 3 compares the order system under a biomass feed-rate disturbance. The two blocks aim to reach a setpoint of 72% bio-oil production, as computed by the Simulink model in MATLAB. The

system begins responding after about 50 s, attributed to a time delay due to thermal inertia and inefficient heat transfer during pyrolysis. Pyrolysis requires sufficient heat to produce bio-oil before biomass can decompose. The sharp rise in the response graph is associated with system underdamping and the operation of a PID controller. The control system reacts strongly to any change in output, leading to an immediate rise and overshoot before it stabilises. This type of response pattern is commonly observed in high-order systems with coupled poles, which can cause oscillations. Table 2 presents the PID tuning values for three different order systems after tuning using the PID Tuner.

Table 2. PID tuning of 0 zero with and without disturbance

Type of Order	PID Controller for 0 Zero			PID Controller for 0 Zero with disturbance		
	1 st Order	2 nd Order	3 rd Order	1 st Order	2 nd Order	3 rd Order
Proportional, K_C	77.49	359.07	400.05	10.52	65.29	0
Integral, K_I	56.35	42.12	0.34	5.28	3.38	0.29
Derivative, K_D	2.45	719.79	1.37	20.45	222.9	0

Figure 2 illustrates that the per cent overshoot of the second-order system is higher than that of the first-order system. This can be attributed to the second-order proportional value being higher than that for the first order, producing larger oscillations and rendering the process system less stable [17]. Furthermore, the first-order system reached the setpoint more rapidly and required less time to achieve steady state than the second-order system. This is because the integral value for the first order is higher than that of the second order. The integral value is inversely proportional to the process response. Thus, a slower response requires less time to achieve the setpoint. The value of the derivative (KD) was lower for the first order compared to the second order. This is because the response KD was highly sensitive to temperature in the process response and required only a small derivative value [18]-[19]. For the amplitude of the third-order system, the results indicate an overdamped, unstable, and oscillatory response. To conclude, the first-order system yielded the best amplitude results, with higher stability, lower overshoot, and greater effectiveness in achieving the setpoint, among other benefits. The values of proportional gain (KC), integral time (KI), and KD were 77.49, 56.35, and 2.45, respectively.

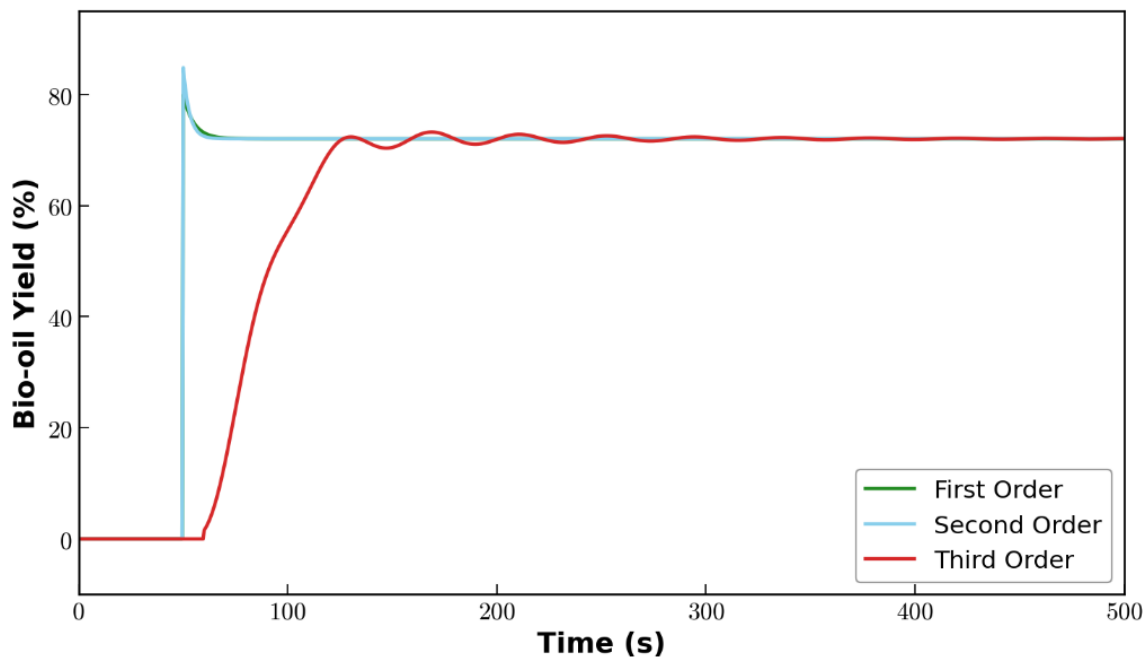


Figure 2. PID controller for 0 zero results

The first-order system produced a lower overshoot than the second-order system, as the higher K_C resulted in smaller oscillations (Figure 3). In addition, the value of K_I for the second-order system was higher than that for the first-order system; a higher K_I value corresponds to a slower process response and a faster time to achieve the setpoint. The third-order system also produced an overdamped, unstable, and oscillatory response due to its high order. The behaviour observed in the third-order system arises from the absence of clearly defined K_C and K_D gains in the controller design. When K_C is set to zero, the primary corrective action that drives the error toward zero and stabilises the closed-loop system is eliminated, a limitation that can produce oscillatory or unstable responses in a higher-order system, even though achieving an overdamped response generally requires only real, negative poles [20-21]. The PID controller introduced disturbances in Figure 3, demonstrating that each order type could achieve the setpoint for bio-oil yield; therefore, the introduction of disturbances into the process does not significantly affect its performance [22]. In summary, the first-order system yielded the most favourable amplitude response, as it was more stable, exhibited less overshoot, and achieved the setpoint more effectively than the other systems. The values of K_C , K_I , and K_D were 10.52, 5.28, and 20.45, respectively.

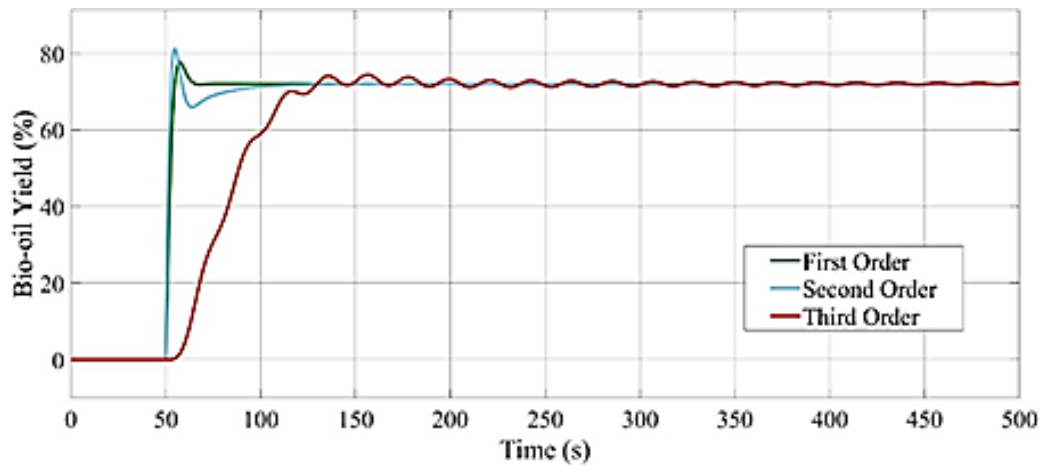


Figure 3. PID controller for 0 zero with disturbance

3.1.2. PID Controller for 1 zero

Figures 4 and 5 show the process response simulation for achieving the setpoint of 72% bio-oil yield. The amplitude results comprise first-, second-, and third-order systems on a scale from 1 to 0. Figure 5, which presents the biomass feed rate disturbance, indicates the difference between the two figures. Furthermore, Table 3 shows the gain parameter values consisting of 1 zero and 1 zero with disturbance for three different order systems using the PID Tuner. As shown in Figure 4, all order systems produce undershoot amplitude. The first-order system produced the highest overshoot value, while the second-order system required the shortest settling time to reach and remain within the range of the setpoint. Therefore, the second-order system yielded the best amplitude results, with the greatest stability, the smallest overshoot peak, the least time to settle, and the shortest time to rise and reach the setpoint. Hence, the final values of K_C , K_I , and K_D were 4.38, 0.14, and -14.54 , respectively. The simulation's observed negative bio-oil yield indicates a physically impossible undershoot, since bio-oil yield cannot be negative. This issue arises because the linear PID model produces transient responses that depend on the initial deviation between the setpoint and the process variable. In higher-order or underdamped systems, large controller gains may cause temporary undershoot and overshoot, resulting in negative simulated outputs [23]. As shown in Figure 5, the second- and third-order components produced unstable, oscillatory amplitudes and could not achieve the target setpoint. Only the first-order system achieved the target setpoint of 72% bio-oil yield. Thus, in a simulation with 1 zero and disturbance occurrence, the first-order system provided the best amplitude results in terms of stability by attaining the approximate setpoint and producing the lowest steady-state error, although it required the longest rise time. Therefore, the final values of K_C , K_I , and K_D were 3.57, 0.105, and 80.39, respectively.

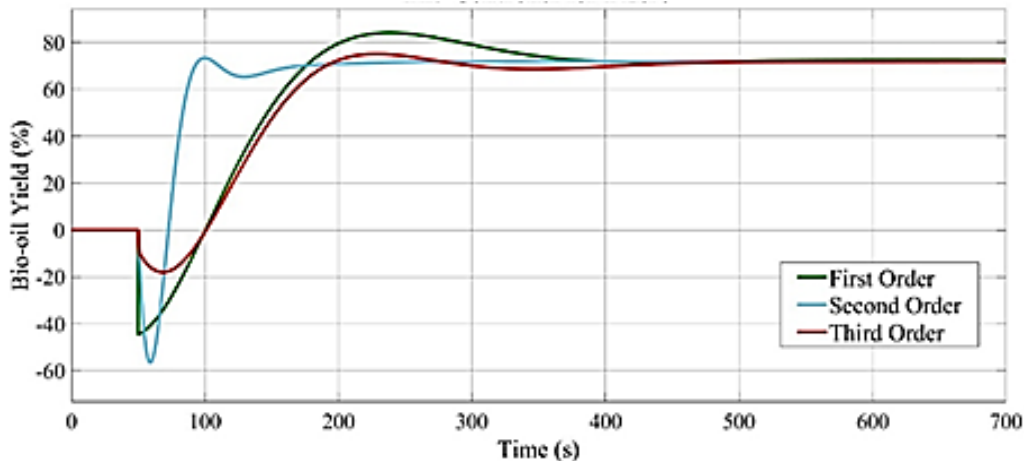


Figure 4. PID controller for 1 zero

Table 3. PID tuning of 1 zero with and without disturbance

Type of Order	PID Controller for 1 Zero			PID Controller for 1 Zero with disturbance		
	1 st Order	2 nd Order	3 rd Order	1 st Order	2 nd Order	3 rd Order
Proportional, K_C	-7.61	4.38	4.74	3.57	7.78	10.65
Integral, K_I	0.19	0.14	0.04	0.105	0.0045	0.087
Derivative, K_D	136.06	-14.54	-271.5	80.39	22.48	0

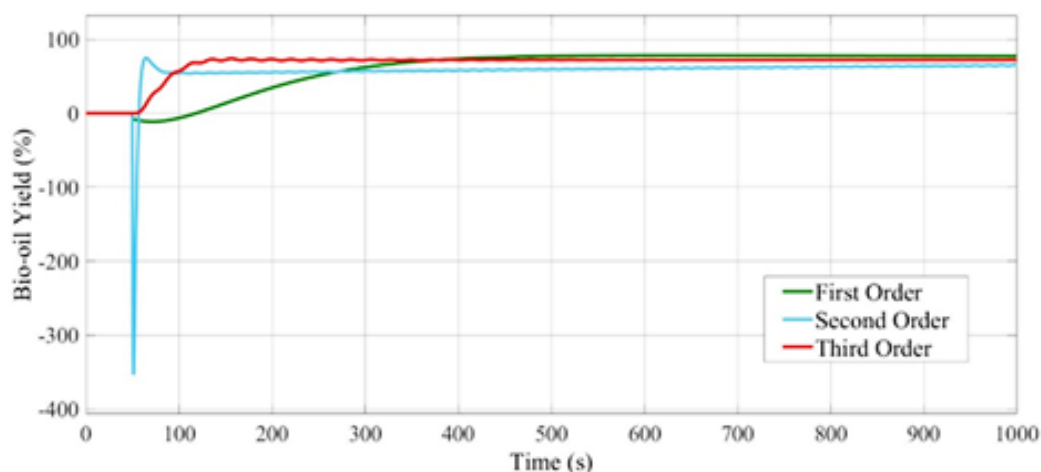


Figure 5. PID controller for 1 zero with disturbance results

4. Conclusion

The PID control mechanism, implemented in MATLAB, can simulate real process data to model the effect of temperature on pyrolysis and achieve the same value as the setpoint. The simulation also achieved the setpoint in the presence of disturbances, and a new transfer function was incorporated into the process. Therefore, the PID Tuner Toolbox was best suited to reject disturbances. In summary, the PID control mechanism could determine the ideal type of order system. The first-order system was identified as the most stable and capable of reaching the setpoint. PID controller simulations showed that the first-order system had the highest stability and produced the desired output of 72% bio-oil yield. The simulation results were obtained both without and with disturbances, indicating that the system can effectively handle process variations. Higher-order transfer functions yielded lower stability and slower responses, making them inefficient for controlling temperature during pyrolysis, especially when rapid adjustments were required to maintain optimal conditions. First-order transfer functions were thus found to be the most appropriate for temperature control in pyrolysis to maximise bio-oil yields.

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Declaration of Competing Interest

The author declares no conflicts of interest.

CRedit Authorship Contribution Statement

A.H.S. Ahmad Tabrani: Analyzed and interpreted the simulation and Simulink development studies.

N.H. Kasmuri: Ideas and conceptualisation of designing this article.

Z. Abdullah: Verification of the simulation methods.

F. Subari: Analysis for the research studies.

S.H. Hanipah: Writing review and verifying the final manuscript.

Availability of Data and Materials

The input and output datasets used in this study were obtained from Ellens CJ and Brown RC (2012) and are available in the original publication.

Ethics Statement

This study did not involve human participants or animal subjects. Therefore, ethical approval was not required.

Generative Artificial Intelligence Declarations

The authors used AI tools only to improve the clarity and language of this manuscript. All content, ideas, and conclusions are the responsibility of the authors.

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