# Modeling study of boiler using oil waste as an energy source

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**Abstract.** Used oil waste is one type of waste that can be used as a source of energy. Waste oil that is used in this research is used as energy source for plasma burner and boiler plants. This final project is aimed at modeling a boiler with 3 input variables and 3 output variables (MIMO - Multiple Input Multiple Output). It's known that this MIMO system still exhibits interactions among the variables. To mitigate these interactions, a decoupler is designed. Subsequently, PID controllers are designed for this MIMO system. The PID parameter values are obtained through modeling using the Ziegler-Nichols method. The modeling is carried out based on the values obtained from the Ziegler-Nichols calculations, which are then implemented in Simulink within MATLAB. The test results indicate that employing a decoupler reduces the interactions between the systems. Therefore, Ziegler-Nichols and heuristic method is needed to find the PID parameter values. By utilizing the heuristic method, the system achieves stability with the value of Kp = 2,1, Ki = 0,005, dan Kd = 0 for the first variable, Kp = 0,0315 Ki = 0, dan Kd = 0 for the second variable, and Kp = 0,007 Ki = 0, dan Kd = 0 for the third variable..

## 1 Introduction

In Indonesia, lubricating oil (engine oil) has a consumption rate of up to 650 million liters annually, with an increase of approximately seven to ten percent each year in the automotive and industrial machinery sectors. If each oil consumption includes 20% of oil being burned or wasted, then the remaining used oil amounts to about 520 million liters per year. Used oil, which is a residue from engine maintenance, generates waste. The waste originating from oil contains various substances that can pollute the air, water, and soil. Pollution caused by this waste is highly hazardous and environmentally contaminating if no effort is made to utilize the waste [1]. Therefore, used oil can be repurposed by converting it into an alternative fuel. Fuel made from oil offers better economic value than kerosene [2].

Utilizing oil as a liquid fuel provides advantages compared to gas-based fuels due to its higher energy density. Liquid fuel utilization also has benefits over solid fuels as it doesn't leave behind ash or combustion residue [3]. Consequently, used oil can be utilized as a fuel, one of which is to serve as burner fuel, such as in stoves [4]. The burner in power generation facilities then heats a steam boiler. Subsequently, the heated water in the boiler produces dry, high-temperature steam used to drive turbines [5].

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The boiler within a power plant has several ontrollable and observable variables. In the power plant under study, there are three input variables for the boiler: pressure, temperature, and level (height), as well as three outputs: an inlet air valve, steam valve, and flame valve. The variables present in a boiler require a system that can regulate and control these variables. One chosen type of control is the PID (Proportional-Integral-Derivative) method. The PID method is still widely used today as it possesses its uniqueness in each controlled plant [6]. The control system using PID is then applied by modeling the boiler system. Modeling is conducted to illustrate various controls present in the boiler system [7].

In previous research, the modeling conducted was only applied to a specific variable, in this case, temperature. In that study, the system successfully controlled the plant and achieved the desired values. This control was achieved using the Ziegler-Nichols method [8]. In another study, modeling was carried out using PID with two methods for multivariable control systems. In this research, the Ziegler-Nichols method demonstrated advantages when compared to the Quarter Decay-Ratio method. The former exhibited a faster rise time to achieve system stability with a better settling time [9]. Another study involved designing a boiler plant. Several observed variables in that research included the amount of steam pressure produced, average exhaust gas temperature, required fuel quantity, and thermal efficiency of the boiler. The results of this study yielded a thermal efficiency of the boiler at 61.65% [10].

This current research is designed to ascertain the system response in a boiler with multiple variables. The modeling conducted will be applied to a boiler system that encompasses several input and output variables, as previously elucidated.

## 2 Methodology

### 2.1 System modelling

The system modelling is determined using fit 1, fit 2, or fit 3 methods. For fit 1, this method employs a tangent line that intersects with the reaction curve. By utilizing this method, the values of $t_0$ and $\tau$ can be determined and directly incorporated into the transfer function of the system. The value of t0 represents the moment when the system starts to increase, while the value of $\tau$ is derived from the difference between the value at the intersection point of the line and t0, symbolized as t3. To find the value of $\tau$, the equation (1) can be utilized.

$$\tau = t_3 - t_0 \quad (1)$$

This method is almost similar to the fit 1 method, with the difference that in this method, the value of $\tau$ is obtained by calculating the difference between t2 and t0, as shown in equation (2) below.

$$\tau = t_2 - t_0 \quad (2)$$

The value of $t_2$ sought is derived from the calculation between two points, namely $t = t0 + \tau$. To obtain the value of $t_2$, the calculation can be done by finding it using equation (3):

$$C(t_2) = 0.632\Delta C \quad (3)$$

This method is an approach that does not rely on the value of the tangent line intersection, as found in the previous two methods. To find the value of t0, the calculation is initiated to determine the value of $t_1$. The sought-after value of $t_1$ arises from the calculation between two points, namely $t_0 + \tau/3$ and $t_0 + \tau$. To obtain the value of $t_1$, the calculation can be performed by searching using equation (4). The calculation to find the value of $t_1$ is as follows:

$$C(t_1) = 0.283\Delta C \quad (4)$$

Then, a calculation is performed to find the value of τ using equation (5):

$$\tau = 3/2\ (t_2 - t_1) \qquad (5)$$

After obtaining the value of τ, the value of t0 can be calculated using the formula present in equation (2). Also in this phase, the value of K is obtained to calculate the decoupling value and simply put into a 3x3 matrix [11].

## 2.2 Decoupler

Using the obtained graphs and transfer functions, the MIMO controller and decoupler design are conducted. Therefore, the value of K is then calculated to find the right pair between them. The value of K then used to determine B, which can be calculated using equation (6):

$$B=K^{-1} \qquad (6)$$

From the equation provided, the obtained decoupling parameter values are from matrix B and can be counted as follows:

$$D_{11}(s) = D_{22}(s) = D_{33}(s) = 1 \qquad (7)$$

$$D_{21}(s) = \frac{B_{21}}{B_{11}} \qquad (8)$$

$$D_{31}(s) = \frac{B_{31}}{B_{11}} \qquad (9)$$

$$D_{12}(s) = \frac{B_{12}}{B_{22}} \qquad (10)$$

$$D_{13}(s) = \frac{B_{13}}{B_{33}} \qquad (11)$$

$$D_{32}(s) = \frac{B_{32}}{B_{22}} \qquad (12)$$

$$D_{23}(s) = \frac{B_{23}}{B_{33}} \qquad (13)$$

## 2.3 PID Controller

There are three parameters in the PID controller. These parameters consist of proportional, integral, and derivative terms. Each parameter has its function and advantages. The parameters are as follows:

### *2.3.1 Proportional control*

Proportional control is a basic controller that calculates the control output value by multiplying the proportional value with the error value from the controller's input, which is the error. In other words, a proportional controller will produce an output signal that is directly proportional to the magnitude of the correction needed by the system to achieve stability. The equation for proportional control is as follows:

$$u(t) = K_P \times e(t) \qquad (14)$$

The proportional control (P) provides a proportional input for a control system with an error. In many cases, using only proportional control can result in a constant error value (stationary error) unless the input value from the control system is zero and the process system's value is equal to the desired value.

### *2.3.2 Integral control*

Unlike proportional control, which multiplies the constant KP by the error value, integral control aims to multiply the integral of the error value over time. The equation for integral control is as follows:

$$u(t) = K_I \times \int_0^t e(t)dt \qquad (15)$$

Ki is the integral constant that attempts to control the system to approach the set point value by multiplying Ki with the integral of the error over time. Ki is usually combined with the KP constant, and this combination has a main advantage: it can eliminate errors that occur in steady-state conditions.

### *2.3.3 Derivative control*

In derivative control, changes in the output that occur at the set point are directly proportional to the rate of change over time of the error signal. Usually, the existing error value is expressed as a percentage of the full output range. The control output is also expressed as a percentage of the full output range. The equation for derivative control is as follows:

$$u(t) = K_D \times \frac{de(t)}{dt} \qquad (16)$$

The derivative control KD is the value of the rate of error change. This control enhances the system's response. Control D is typically used alongside Control P or PI as PD or PID control. However, excessive application of Control D can lead to system instability. The response from PD control provides a faster-rising response compared to a P controller. Essentially, Control D exhibits the characteristics of a high pass filter on the error signal. By using derivative control, the system can predict future errors and anticipate them. The derivative controller knows that the rate of change of error is constant, and the control output signal will be provided to the correction element [12].

## 2.4 Ziegler Nichols

The Ziegler-Nichols method is one of the tuning methods proposed by two individuals, namely Ziegler and Nichols. Ziegler and Nichols introduced this method in early 1942. This method has a tuning formula obtained by applying a first-order plus dead time (FOPDT) model to five plant models. The Ziegler-Nichols method is based on a closed-loop system. The plant being tuned is arranged in series with a PID controller [13].

There are two ways to determine PID values using the Ziegler-Nichols method. One of these methods is the step response method. This method is a classic approach that has been around since 1942, yet it is still widely used in industrial processes as a foundation for tuning control systems. The ZieglerNichols method requires a stable system process. In the step response method, there are two parts symbolized by the variables L and T [14]. These variables are obtained by drawing a tangent line at the slope point located at the maximum step response value, as seen in Figure 1.

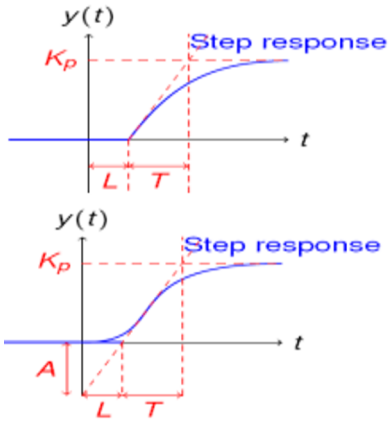


**Fig. 1.** Tangent line of Ziegler-Nichols tuning first method**.**

The PID parameters, consisting of proportional, integral, and derivative terms, are then tuned using the formulas recommended by Ziegler-Nichols, as shown in Table 1.

**Table 1.** Tuning table using Ziegler-Nichols.

| Controller | Kp | Ti | Td |
|---|---|---|---|
| P | T/L | ∞ | 0 |
| PI | 0.9T/L | L/0.3 | 0 |
| PID | 1.2T/L | 2L | 0.5L |

### 2.5 Heuristic

Heuristic methods are approaches used to solve problems through trial and error. These methods can be designed by making adjustments to variable values based on plant performance. In the design of heuristics for PID, a search is first conducted for the values of Kp, Ki, and Kd through several stages. These stages involve applying a proportional (P) controller first, followed by assigning an integral (I) controller, and finally incorporating a derivative (D) controller. The allocation and determination of these values are adjusted according to the characteristics of the obtained system response [15].

## 3 Results

### 3.1 System modeling

The modeled system and determined transfer function are as follows:

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 0{,}784\frac{e^{-0{,}5165s}}{0{,}3135s + 1} \quad (17)$$

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 0{,}00275\frac{e^{-0{,}25s}}{1{,}50 + 1} \quad (18)$$

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 5{,}41\frac{e^{-0s}}{1{,}4s + 1} \quad (19)$$

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 1{,}37\frac{e^{-0{,}1s}}{2{,}4s + 1} \quad (20)$$

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 0{,}034\frac{e^{-0{,}5s}}{6s + 1} \quad (21)$$

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 0{,}185\frac{e^{-1s}}{3{,}5s + 1} \quad (22)$$

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 0{,}5839\frac{e^{-0{,}5s}}{15{,}5s + 1} \quad (23)$$

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 0{,}045\frac{e^{-6s}}{10{,}5s + 1} \quad (24)$$

$$G(s) = K\frac{e^{-t_o s}}{\tau s + 1} = 0{,}9\frac{e^{-25s}}{3{,}5s + 1} \quad (25)$$

In this stage, simulations are conducted on equations (17) to (25), resulting in sequential graphs as illustrated in Figures 2 to Figures 10.

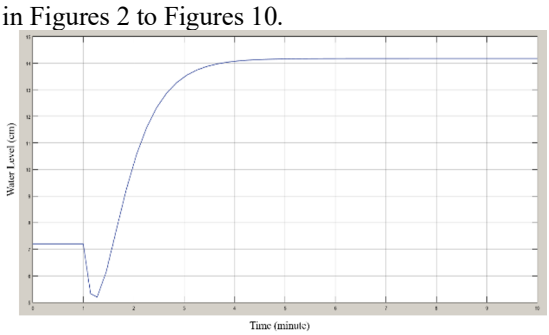


**Fig. 2.** Modelling result on equation (17).

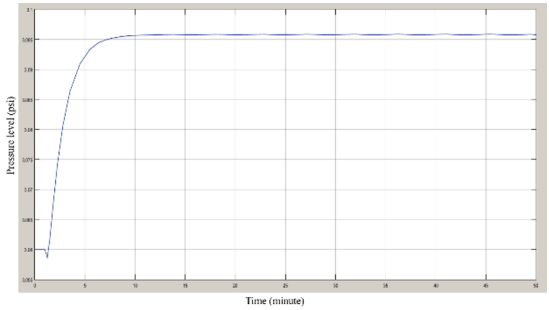


**Fig. 3.** Modelling result on equation (18).

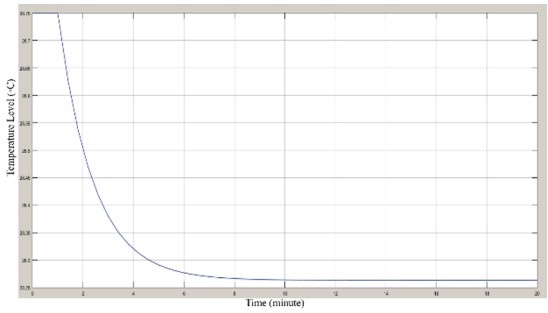


**Fig. 4.** Modelling result on equation (19)

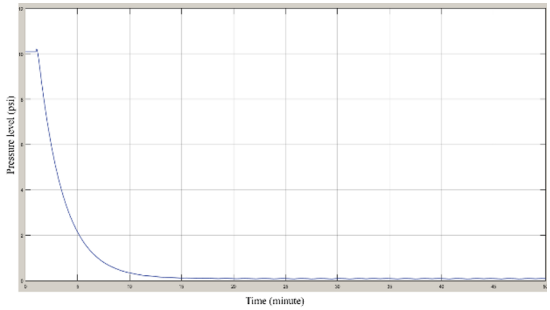


**Fig. 5.** Modelling result on equation (20).

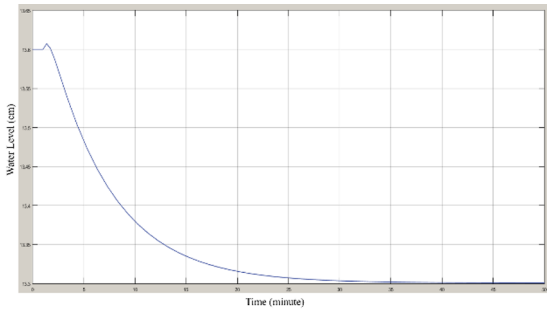


**Fig. 6.** Modelling result on equation (21).

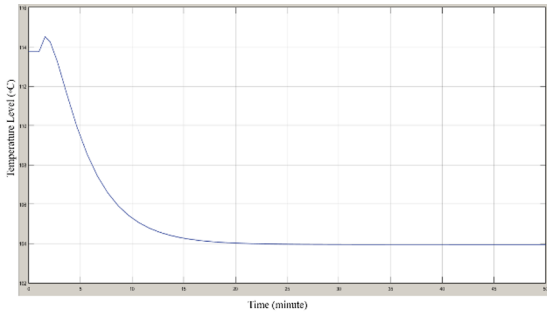


**Fig. 7.** Modelling result on equation (22).

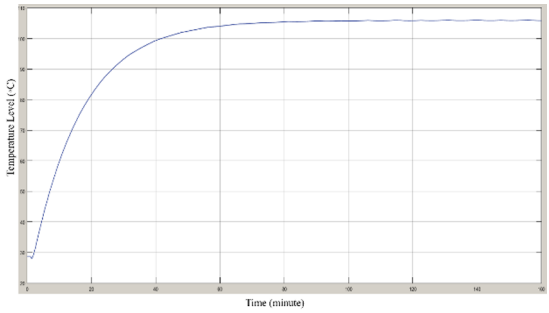


**Fig. 8.** Modelling result on equation (23).

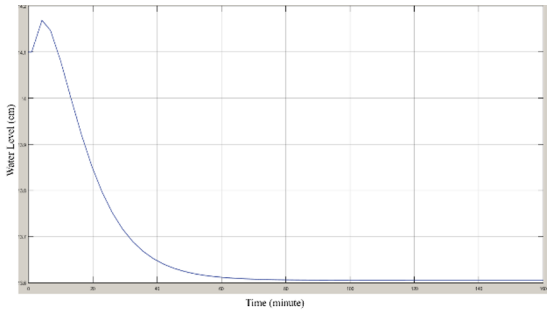


**Fig. 9.** Modelling result on equation (24).

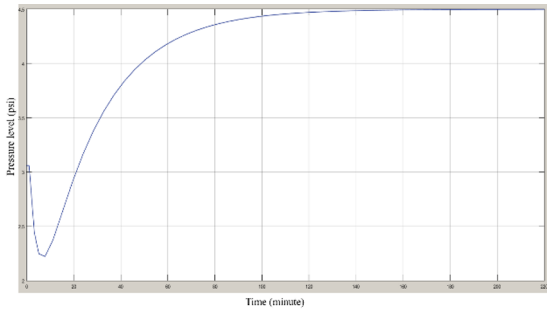


**Fig. 10.** Modelling result on equation (25).

### 3.2 Design and modeling with decoupler

In this section, the decoupler design is carried out using the obtained value of K from the calculations in the previous stage. The value of K is then inserted into a 3x3 matrix in the following order:

$$K = \begin{bmatrix} 0{,}784 & 0{,}0872 & 5{,}41 \\ -0{,}034 & -1{,}37 & -0{,}185 \\ -0{,}045 & 0{,}9 & 0{,}5839 \end{bmatrix} \quad (26)$$

Using equation (26), the calculation of the value of B is performed, which is the inverse of the matrix K in equation (6). The calculation is conducted using the MATLAB program, resulting as follows:

$$B = \begin{bmatrix} 0{,}6362 & -4{,}888 & -7{,}4438 \\ -0{,}0283 & -0{,}7043 & 0{,}0391 \\ 0{,}0927 & 0{,}7088 & 1{,}0787 \end{bmatrix} \quad (27)$$

By obtaining the value of B, then the calculation of the decoupler could be done using equation (7) to (13). The results if the calculations are then also inserted into a 3x3 matrix in the following order:

$$\begin{bmatrix} 1 & 6{,}815 & -6{,}9 \\ -0{,}0444 & 1 & 0{,}03622 \\ -0{,}1457 & -1{,}0063 & 1 \end{bmatrix} \quad (28)$$

Also, the value 1 for the matrix of the decoupler shows that those are the right pair. That equation would be used for the next step of the research, the Ziegler-Nichols method.

### 3.3 PID tuning using Ziegler-Nichols method

In this section, using appropriate pairs, the PID values can be determined using the PID calculations. The values of T and L are obtained by drawing the tangent line as shown in Figure 1. The design of PID values is as follows:

#### *3.3.1 PID values for the level and air inlet valve pair*

Using the graph from fit 3, a tangent line is drawn to determine the values of L and T, as shown in Figure 11.

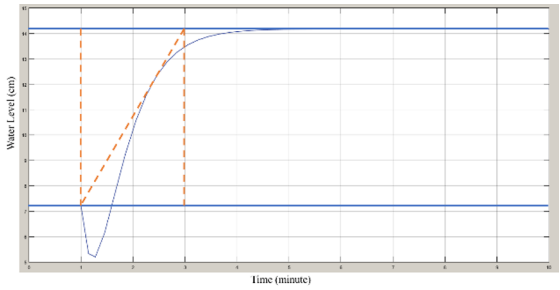


**Fig. 11.** Determination of L and T values in the pump on condition.

By plotting the line on the graph, the value of T = 1.8 and the value of L = 1 are obtained. Then, the values for $Kp$, $Ki$, and $Td$ are 2.16, 0.5, and 0.5.

#### *3.3.2 PID values for the pressure and steam valve pair*

Using the graph from fit 2, a tangent line is drawn to determine the values of L and T, as shown in Figure 12.

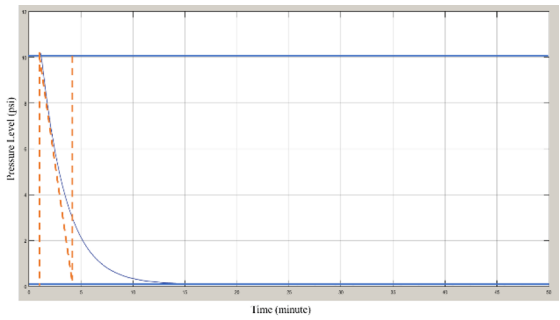


**Fig. 12.** Determination of L and T values in valve on condition.

By plotting the line on the graph, it is known that the value of T = 3 and the value of L = 1. Then, the values for $Kp$, $Ki$, and $Td$ are 3.6, 0.5, and 0.5.

### *3.3.3 PID values for the temperature and fire valve pair*

Using the graph from fit 2, a tangent line is drawn to determine the values of L and T, as shown in Figure 13.

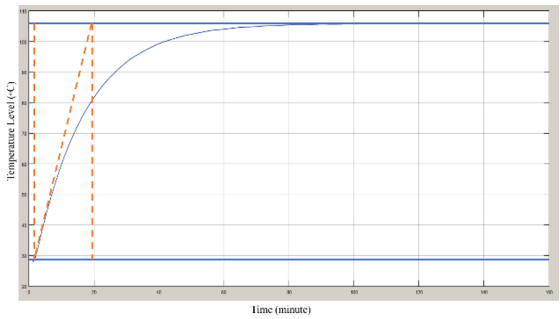


**Fig. 13.** Determination of L and T values when the stove is on.

By plotting the line on the graph, the value of T = 18 and the value of L = 2 are obtained. Then, the values for $Kp$, $Ki$, and $Td$ are 10.8, 0.25, and 1. Subsequently, after obtaining the PID, decoupler, and transfer function values, simulations of the design results are conducted. These simulations are performed using the MATLAB application. The graphs depicting the modeling results with the obtained PID values from the previous calculations are shown in Figures 14 to 16.

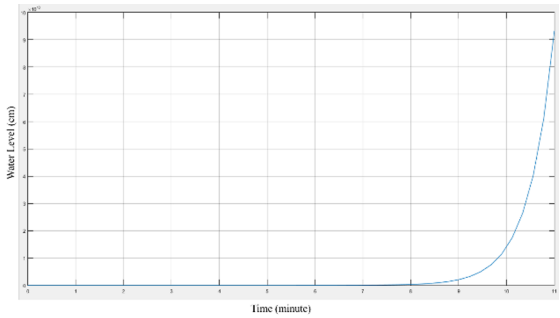


**Fig. 14.** Modeling graph of water when the pump is on.

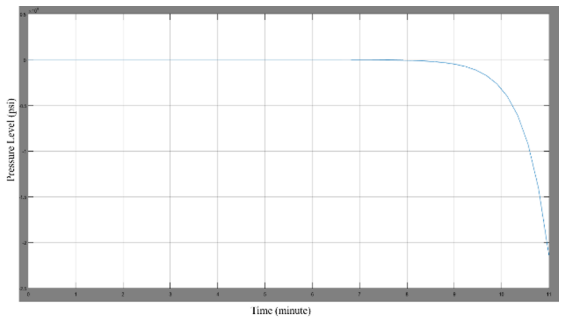


**Fig. 15.** Pressure graph when the valve is on.

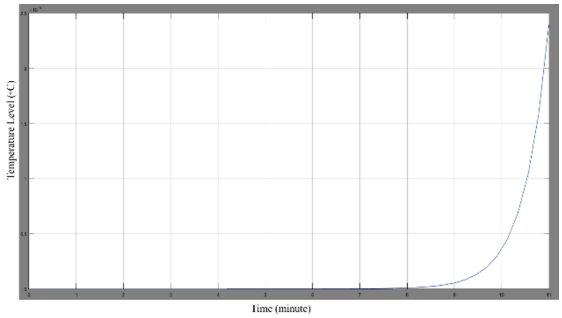


**Fig. 16.** Temperature graph when the stove is on.

In these graphs, it can be observed that the desired system stability is not achieved. Therefore, a heuristic method needs to be applied to search for PID values that can attain the desired outcomes.

### 3.4 PID tuning using heuristic method

In this stage, PID values are designed using the heuristic method. This design process aims to obtain the optimal PID values for the system. The heuristic design begins by initiating experiments with assigned values for each PID parameter and observing the resulting graphs displayed by the scope in MATLAB Simulink.

Initially, tuning is performed on the PID values that affect the system's behaviour when the pump is on, the valve is off, and the stove is on. Through this tuning process, the best values are determined as follows: Kp = 2.1, Ki = 0.005, and Kd = 0. The graphical outcomes of the tuning process can be observed in Figure 17.

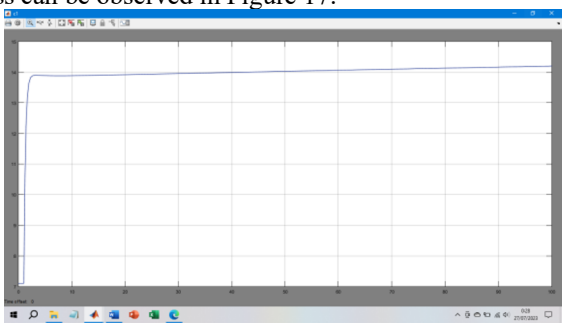

**Fig. 17.** Tuning result for Kp = 0,0315 Ki = 0, dan Kd = 0.

Furthermore, the system is tuned under conditions where the valve is on, the pump is off, and the stove is off. The optimal values obtained from this tuning process are Kp = 0.0315, Ki = 0, and Kd = 0, respectively. The graphical results of this tuning can be observed in Figure 18.

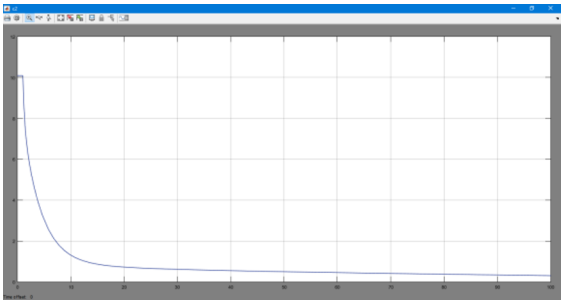

**Fig. 18.** Tuning result for Kp = 0,0315 Ki = 0, dan Kd = 0.

Next, the system is tuned under conditions where the valve is on, the pump is off, and the stove is off. The best values obtained from this tuning process have PID values of Kp = 0.0315, Ki = 0, and Kd = 0, respectively. The displayed graphical results can be seen in Figure 19.

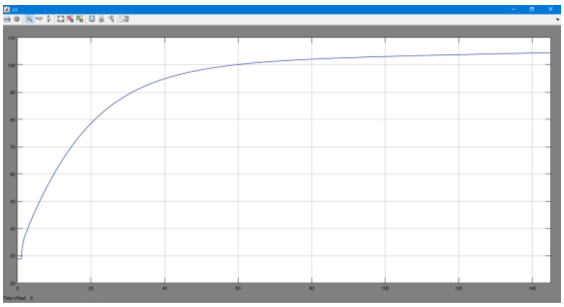

**Fig. 19.** Tuning result for Kp = 0,007 Ki = 0, dan Kd = 0.

For the first variable, concerning water level increase, it is found that the value of rise time (tr) is 0.92, and the settling time (ts) is 50. For the second variable, it is found that the rise time (tr) is 11.7 and the settling time (ts) is 110. Similarly, for the third variable, the rise time (tr) is determined as 48.25, and the settling time (ts) is 120.

## 4 Conclusions

Based on the testing and modeling results obtained from the data collection, the following conclusions can be drawn:
1. The data collection process was appropriate, but there were some challenges in stabilizing the temperature and pressure responses. This issue can be addressed by carefully designing auxiliary lines to ensure proper modeling.
2. The modeling method using fit 2 is superior, as it provides a more accurate determination of $t_0$ and $t_2$ values.
3. Selecting the appropriate decoupler pairs involves choosing pairs with Relative Gain Array (RGA) values having the largest positive values for each column and row.
4. Decoupling can effectively reduce interactions between variables.
5. The tuning performed using the heuristic method finds that the system achieves stability with the value of Kp = 2,1, Ki = 0,005, dan Kd = 0 for the first variable, Kp = 0,0315 Ki = 0, dan Kd = 0 for the second variable, and Kp = 0,007 Ki = 0, dan Kd = 0 for the third variable.

## References

1. M. Lutfi, JST (Jurnal Sains Ter. **7**, 57 (2021)
2. A. W. Nuruddin, H. Suwardana, A. Kalista, and N. Wicaksono, Pros. SNasPPM **5**, 108 (2020)
3. V. Raghavan, *Combustion Technology: Essentials of Flames and Burners* (Springer Nature, 2021)
4. K. E. Mahardhika, D. T. Santoso, and K. Kasiadi, JTM-ITI (Jurnal Tek. Mesin ITI) **4**, 94 (2020)
5. I. Y. N. Riadessy, Surabaya Inst. Teknol. Sepuluh Nop. (2015)
6. W. Bolton, *Instrumentation and Control Systems* (Newnes, 2021)
7. Arif, **2**, (2017)
8. P. M. Wibowo, *Kontrol PID Untuk Mengatur Lebih Dari Satu Variabel Pada Pemodelan Heater, Repository.* (2009)
9. A. C. R. Gunadhi, A. Sudrajat, and K. R. Lestari, J. Ilm. GIGA **21**, 69 (2019)
10. W. Broto and A. Prasetyowati, in *Pros. Semin. Nas. Fis.* (2015), pp. SNF2015-VI
11. J. R. Manalu, E. M. Tarigan, and R. Nainggolan, SINERGI POLMED J. Ilm. Tek. Mesin **2**, 16 (2021)
12. C. A. Smith and A. B. Corripio, *Principles and Practices of Automatic Process Control* (John wiley & sons, 2005)
13. V. Kumar and A. Patra, Int. J. Electr. Electron. Eng. **8**, 559 (2016)
14. A. Ma'arif, *Dasar Sistem Kendali Pemodelan, Pengendalian, Analisis, Simulasi, Dan Implementasi* (UAD PRESS, 2021)
15. G. G. Iranda, (2021)