

Temperature Control Using Labview-Based Fuzzy Logic on a Calorimeter for Physics Experiments

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Abstract

In this research, an analysis of temperature regulation was conducted on the calorimeter used for Physics practicum using the Labview controller. The purpose of this study is to obtain a stable calorimeter temperature output so that it makes it easier for the practicum to be carried out. The object to be measured is the output temperature of the calorimeter which is heated and detected by the LM-35 temperature sensor. NI-DAQ USB 6008 is used as the data acquisition device, and is connected to Labview software. The data collection process was carried out by comparing 5 tests, including testing without a Fuzzy controller, testing a Fuzzy controller with 74 percent, 80 percent, 89 percent, 90 percent from PWM maximum defuzzification. The final results show that temperature regulation on the calorimeter with Fuzzy logic is quite effective with 90 percent defuzzification, because the temperature can reach the set point value with a settling time of 40 minutes and has a steady state error of 1.1 percent.

Keywords: Temperature; Calorimeter; Labview; Control; Fuzzy; PWM

1. Introduction

Physics laboratory activities play an essential role in helping students understand fundamental scientific concepts through direct experimentation and observation. One of the most important instruments used in thermodynamics experiments is the calorimeter, which enables students to study heat transfer, energy conservation, specific heat capacity, and enthalpy changes quantitatively. The development of electronic calorimeters for educational applications has significantly improved students' ability to perform thermochemical analysis and obtain more accurate experimental results [1] Furthermore, improvements in calorimeter design for undergraduate laboratories have shown that modern calorimetric systems can enhance measurement consistency and experimental efficiency [2].

However, conventional calorimeters used in physics laboratory practices still encounter several challenges related to measurement uncertainty and temperature instability. Experimental studies have shown that low-cost educational calorimeters often experience significant errors due to environmental temperature fluctuations, heat losses, and limited thermal insulation performance [3]. To overcome these limitations, recent developments in educational calorimeter design have focused on improving thermal isolation and structural efficiency while maintaining affordability for laboratory implementation [4].

Accurate temperature regulation is one of the most critical factors in calorimetric measurements. Research on heat conduction calorimeters has demonstrated that stable temperature conditions are necessary to obtain accurate heat capacity measurements of solid and liquid samples [5]. Similarly, microcalorimeter systems designed for thermal energy analysis require precise thermal equilibrium to ensure reliable heat measurement results [6]. These findings indicate that temperature stability directly influences the accuracy and repeatability of calorimetric experiments.

In addition to improving measurement accuracy, modern calorimeter systems have also been developed to support sustainable and accessible laboratory education. Recent studies on 3D-printed calorimeters show that advanced fabrication methods can reduce manufacturing costs while maintaining acceptable thermal performance for educational experiments [7]. However, maintaining temperature stability remains a major challenge in these systems, particularly during repeated experimental use.

To address this issue, several researchers have proposed integrating automatic temperature control mechanisms into calorimetric systems. Precision temperature control systems have successfully demonstrated stable thermal conditions during long-term experimental measurements [8]. Moreover, advanced temperature estimation methods for distributed calorimetric systems have improved thermal monitoring accuracy across wider operating ranges [9]. Calibration techniques for temperature sensors have also been developed to minimize measurement errors and improve system reliability in calorimetric applications [10].

In recent years, fuzzy logic control has been widely applied in thermal process systems due to its capability to handle nonlinear behavior, parameter uncertainty, and external disturbances. Previous studies have demonstrated that fuzzy-based temperature control provides better overshoot reduction and faster settling time compared with conventional PID controllers in heating applications [11] [12]. In laboratory-scale thermal systems, adaptive fuzzy controllers have also shown improved temperature stability and measurement consistency under varying operating conditions [13] [14]. Furthermore, fuzzy control has been reported to reduce energy consumption in embedded heating systems while maintaining thermal precision [15]. Comparative studies consistently indicate that fuzzy logic controllers outperform conventional methods in disturbance rejection and dynamic thermal stabilization [16] [17] [18] [19]. Recent research has also shown that optimization of fuzzy membership functions can further enhance temperature control accuracy in educational laboratory equipment [20].

Based on these studies, the development of an automatic temperature regulation system for calorimeters in physics laboratory applications is highly necessary. Such a system is expected to improve measurement accuracy, reduce experimental uncertainty, and provide a more effective learning environment for students studying thermodynamics and heat transfer.

2. Material and methods

2.1 Block Diagram Systems

Figure 1 explains that the LM-35 temperature sensor will detect the temperature from the calorimeter which will then be forwarded to the NI DAQ USB 6008, then processed by converting data from analog to digital so that it is displayed and processed in the Labview software. A calorimeter is a heat exchange device between the system inside and its environment which is limited as far as possible. The calorimeter is used for various measurements, such as specific heat, distillation heat, melting heat, and others. The heater on the calorimeter is connected to the L298N driver which functions to increase the power coming from the NI-DAQ USB 6008. On the L298N, the enable pins A and B are used to control the motor speed, input pins 1 to 4 are used to control the direction of rotation. The output pin on the L298 13 IC is connected to the DC motor which was previously connected via an H-Bridge diode. The increase in temperature due to heat in a certain amount is influenced by the heat capacity of the receiving object. Then the temperature output that has been set on the NI-DAQ USB 6008 will be obtained. After that, the data output is amplified by the L298N driver using the PWM method, so that it is able to heat the calorimeter to the specified temperature until it is stable.

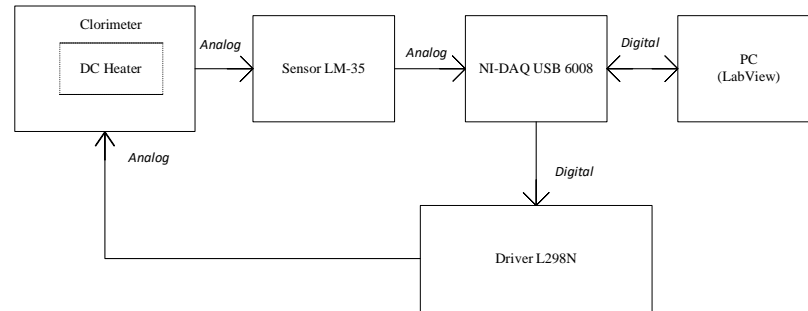


Figure 1. Diagram Block

The first step in designing this software is graphical coding using LabView. Because LabView is a graphical programming language, the required hardware is wired and connected according to the sequence described in the Diagram Block above, making coding easier for researchers. Then, LabView sets the temperature range parameters for each input value, the input delta, and the output. Next, the fuzzification process organizes and transforms the predetermined input data into membership degrees. The initial temperature data is represented by the membership functions "cold," "warm," "slightly hot," and "hot," using a trapezoidal membership function.

The fuzzy logic rules are set based on the membership functions created in the previous step. The division of these fuzzy logic rules serves to connect the input and output. The AND operation is used. The next step in designing this software is defuzzification, the final step in fuzzy logic, which aims to convert each inference result expressed in the form of a fuzzy set into real numbers so that the results can be obtained and displayed. Then, upload the fuzzy logic program to the LabView graphical program. After that, the running program is monitored for errors. If errors occur, the program is checked and changes are made to the error-prone program. If no errors occur, the program is considered complete, and the data can be obtained for analysis. The flowchart is shown in figure 2.

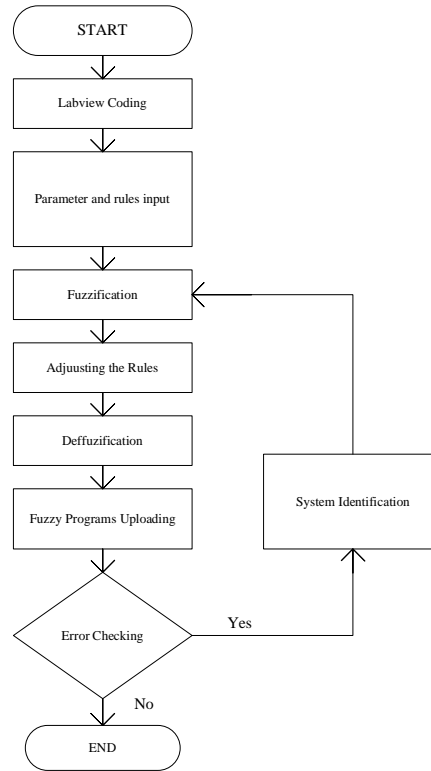


Figure 2. Flowchart System

From Figure 2 above, the software design flow in this study can be explained. The first process carried out in this software design is to carry out graphical coding with LabVIEW, this is because LabVIEW is a graphical-based programming language, so what is done is to do wiring according to the required hardware and then connect it according to the sequence of flows that have been explained in the hardware flow above so that it makes it easier for researchers to do coding. After that, the LabVIEW software sets the temperature range parameters for each input value, input delta, and output. Next, carry out the fuzzification process where this process organizes and changes the input data that has been determined in the form of membership degrees, in the form of initial temperature data with cold, warm, slightly hot, and hot membership functions in the form of trapezoidal membership functions. The Labview system Diagram is shown in Figure 3, with the hardware configuration shows in Figure 4.

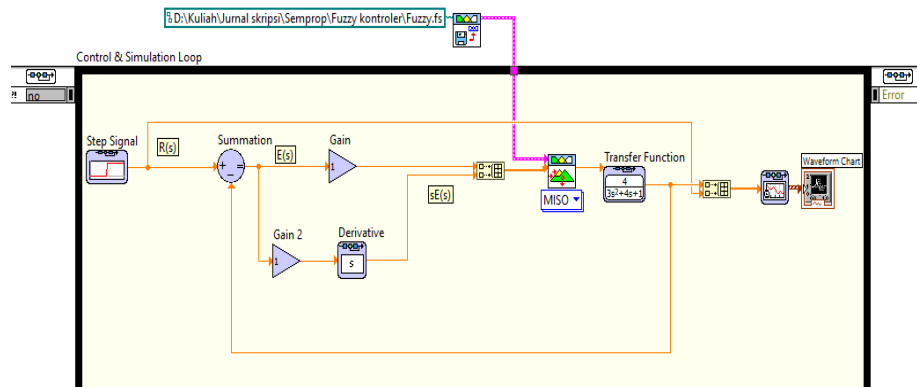


Figure 3. Labview System Diagram

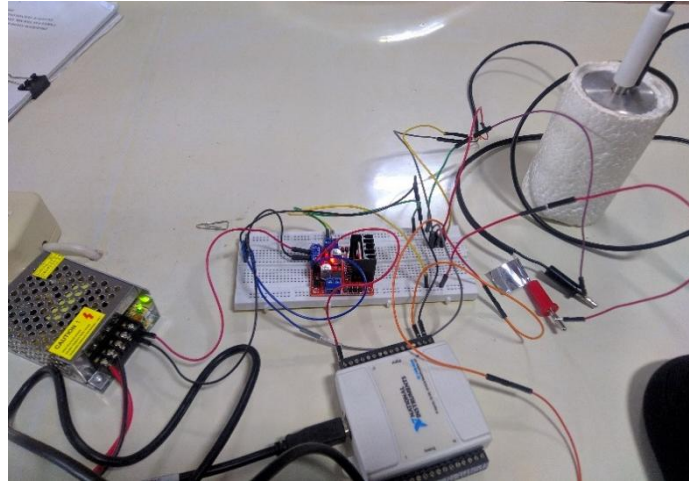


Figure 4. Hardware Configuration

2.2 Fuzzy Logic Controller Design

To achieve stable temperature regulation in the calorimeter system, a Fuzzy Logic Controller (FLC) was implemented. The controller was designed to adjust the heater power automatically based on the temperature error and the rate of error change. Compared with conventional on-off control, fuzzy logic provides smoother control action, reduces overshoot, and improves temperature stability in nonlinear thermal systems. The proposed fuzzy controller uses two input variables, namely Error (E) and Delta Error (dE). The temperature error represents the difference between the desired temperature and the measured temperature, defined as:

$$E = T_{set} - T_{actual} \quad (1)$$

where T_{set} is the temperature setpoint, and T_{actual} is the measured temperature obtained from the temperature sensor. Three fuzzy linguistic variables were assigned to the error input, NB (Negative Big), the actual temperature is higher than the setpoint, Z (Zero), the actual temperature is close to the setpoint, and PB (Positive Big), the actual temperature is lower than the setpoint. These membership functions represent the thermal condition of the calorimeter during the heating process.

The delta error describes the change in error between two consecutive sampling periods and is expressed as:

$$dE = E(k) - E(k - 1) \quad (2)$$

where $E(k)$ is the current error and $E(k - 1)$ is the previous error. Three linguistic variables were defined for delta error, NB (Negative Big): the error is decreasing rapidly, Z (Zero): the error is stable, PB (Positive Big): the error is increasing. The use of delta error enables the controller to predict the thermal trend of the system and improve dynamic response.

The output of the fuzzy controller is the heater power level, represented as Pulse Width Modulation (PWM) percentage. Three fuzzy output sets were defined, L (Low) with 20% heater power, M (Medium) with 50% heater power, and H (High) with 90% heater power. These output levels determine the heating intensity required to maintain the calorimeter temperature near the desired setpoint.

A 3×3 rule base was constructed based on expert knowledge of thermal system behavior. The corresponding IF-THEN rules are defined as follows:

- R1: IF Error is NB AND dError is NB THEN Output is Low.
- R2: IF Error is NB AND dError is Z THEN Output is Low.
- R3: IF Error is NB AND dError is PB THEN Output is Medium.
- R4: IF Error is Z AND dError is NB THEN Output is Low.
- R5: IF Error is Z AND dError is Z THEN Output is Medium.
- R6: IF Error is Z AND dError is PB THEN Output is High.
- R7: IF Error is PB AND dError is NB THEN Output is Medium.
- R8: IF Error is PB AND dError is Z THEN Output is High.
- R9: IF Error is PB AND dError is PB THEN Output is High.

These rules allow the controller to provide appropriate heating action according to the thermal condition of the calorimeter.

3. Results and discussion

Testing Without Fuzzy Controller

This test aims to determine the time required to reach a predetermined temperature and then stabilize. Two programs are run: a sensor program with PWM settings only. By setting the PWM output with a 30% duty cycle to heat the calorimeter, the temperature will be read by the sensor. This can be seen in Figure 5.

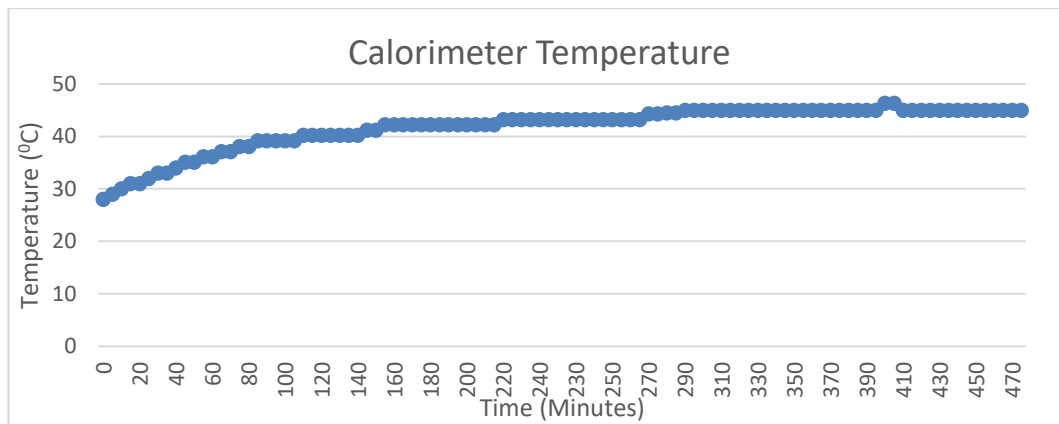


Figure 5. Temperature of Calorimeter without Fuzzy Controller

Based on Figure, the settling time, or the time to reach a value before the stable value itself, can be obtained, namely in the 280th minute at a temperature of 44.5 °C. The temperature reached the set point for 5 hours or in the 300th minute, then in the 400th minute the temperature increased to 1.1 °C, namely at a temperature of 46.1°C. However, it only lasted 5 minutes until the temperature dropped back to 45 °C. after which the temperature stabilized. This is because there is no fuzzy controllers so it takes a very long time to reach a stable temperature.

The output using 74% Percent Defuzzification Test

Defuzzification is the final step in a fuzzy logic system. Its purpose is to convert the previously fuzzy results, displayed in the form of a fuzzy set, into a real number. In this test, the initial defuzzification value is 74 percent as the duty cycle for the PWM, so that its output will heat the calorimeter. Then, when the temperature equals the set point, it is reduced to 49 percent to maintain a stable temperature.

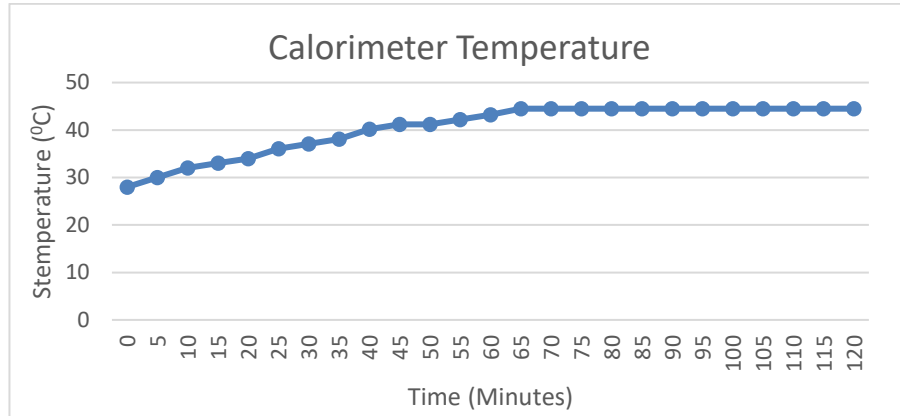


Figure 6. Temperature of Calorimeter with 74% Defuzzification

From Figure 6, it can be seen that the temperature value reached the set point in the 80th minute and after that the temperature stabilized, the temperature value read by the sensor fluctuated between 44 °C and 45 °C, so the researcher took the middle value, namely 44.5 °C, as a stable temperature value. The settling time in this test was achieved at 75 minutes with a temperature of 44.3 °C. Based on calculations, the steady-state error (Ess) was small and accurate. However, it is less suitable for physics experiments due to the slow response time.

The output using 80% Percent Defuzzification Test

In this test, the researchers narrowed the input fuzzification range to -0.2 to 0.2. This was because the previous test obtained a difference of 0.17 between the set point and the voltage provided by the sensor at rest or at 28°C.

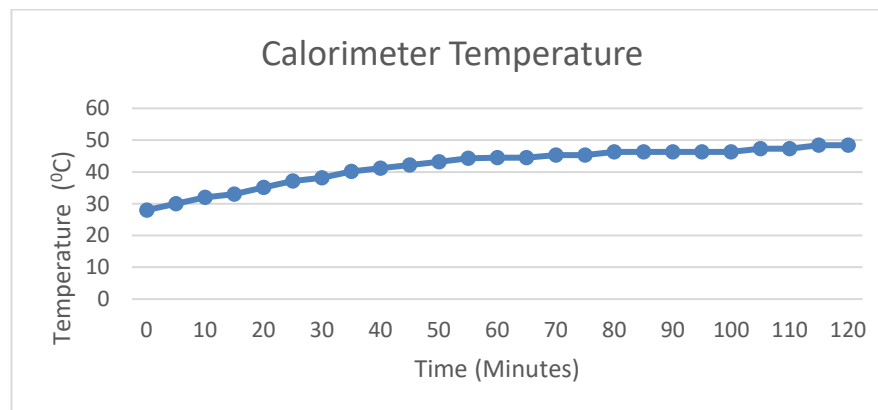


Figure 7. Temperature of Calorimeter with 80% Defuzzification

Figure 7 shows the temperature reaching the set point at minute 60, but this only lasted for 5 minutes. Afterward, the temperature rose again to 48.4°C. This is because a duty cycle exceeding 50% was unable to maintain a stable temperature at 45°C. Based on the calculations above, the measurement accuracy was still good, but it had a high steady-state error. Therefore, it was ineffective as a reference for physics experiments, and the researchers stopped the measurement because the temperature was still likely to rise.

The output using 89% Percent Defuzzification Test

In this test, the researchers used fuzzification for the temperature delta input, the same as before. The only change was the fuzzification at the output to increase the resulting output value. This can be seen in Figure 8.

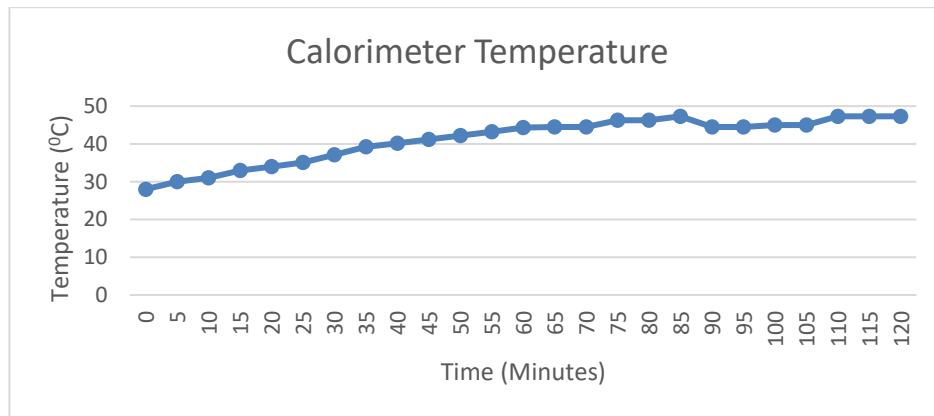


Figure 8. Temperature of Calorimeter with 89% Defuzzification

Figure 8 shows the temperature value at the set point at the 45th minute, but it remained the same as the previous test, lasting only 10 minutes. Afterward, the temperature rose again to 47.3°C, but then dropped again to 45°C. This was due to the delta input membership function limit having fallen back to -0.025, causing the temperature to drop. However, the duty cycle was still large, and the calorimeter continued to heat, causing the temperature to rise again after 10 minutes. These calculations yield a fairly large steady-state error, with greater measurement accuracy than the previous test. However, it is still ineffective as a reference for future physics experiments.

The output using 90% Percent Defuzzification Test

In this test, changes in fuzzification are visible in Figure 9. This test achieved a faster settling time, at 40 minutes, and the temperature reached the set point at 45 minutes. Based on these calculations, the steady-state error value is small and the measurement accuracy is good. The graph is shown in figure 9.

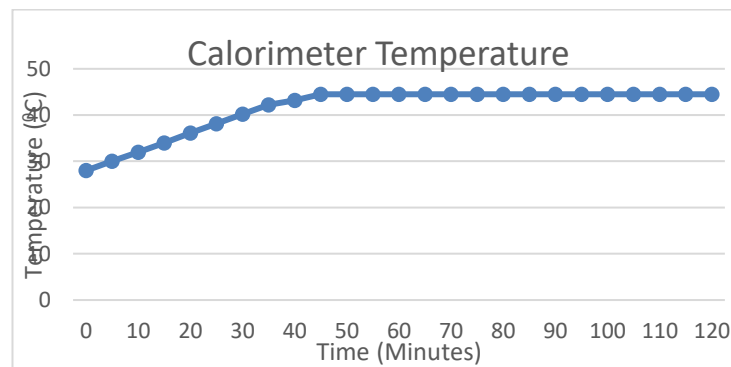


Figure 9. Temperature of Calorimeter with 90% Defuzzification

Among all configurations, the 90% defuzzification test provided the best overall performance. The rise time decreased drastically to 40 minutes and the settling time to 45 minutes, representing the fastest and most stable response. In addition, the overshoot was only 1.8%, which is the lowest among all tests, and the steady-state error reached 1.1%, indicating high accuracy in maintaining the desired setpoint. Therefore, the 90% defuzzification configuration can be considered the optimal tuning parameter for this fuzzy control system because it achieved the best balance between response speed, stability, and accuracy. Overall, the results demonstrate that fuzzy logic control effectively enhances system performance by improving transient response characteristics and reducing steady-

state error compared to the conventional controller. The performance comparison is shown in table 1.

Table 1. Performance Comparison

Controller Type	Time rise	Time settling	Overshoot	Error steady state
Without Fuzzy	280 minutes	300 minutes	12.4 %	3.8 %
Defuzzification at 74% test	70 minutes	75 minutes	2.4 %	1.57%
Defuzzification at 80% test	60 minutes	65 minutes	7.5%	8.23 %
Defuzzification at 89% test	45 minutes	90 minutes	2.6 %	5.11 %
Defuzzification at 90% test	40 minutes	45 minutes	1.8 %	1.1 %

4. Conclusion

The previous research [20] gave more emphasize in optimizing the fuzzification system in order to optimize the performance. In this research, the tuning is based on the different performance and power at the defuzzification system. It is shown that by adjusting the parameter in the defuzzification system, the performance could be optimized. The most effective defuzzification test was 90% as it had the fastest settling time at 40 minutes and a steady-state error of 1.1% with an accuracy level of 98.9%. Furthermore, the system block lacked a delay unit. The system response without a controller had a long delay of up to 280 minutes to reach the set point, and there was a 5-minute temperature increase, from 400 to 405 minutes. However, with a controller, the system response was faster, reaching the set point in 45 minutes and stabilizing thereafter.

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