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Water Temperature Control System with PID Control Method and Fuzzy Logic Based on SCADA

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Abstract – *Heating water to a certain temperature is widely used in the chemical and food industries to improve product quality. This research compares the Ziegler-Nichols PID controller and Sugeno fuzzy logic to determine the precise and optimal control method for nonlinear water temperature affected by room temperature disturbances. The experimental method was conducted on the OMRON CP1H PLC with RTD PT-100 and DPT sensors to measure temperature and water level. SCADA Wonderware InTouch is used for monitoring, control, and data logging, as well as system stability analysis through transient response with water as the test parameter. The results show that the Sugeno fuzzy controller achieves an accuracy of 96.03% compared to the MATLAB simulation, and has a faster transient response with a delay time difference of 8 s, rise time of 26 s, settling time of 5560 s, maximum overshoot of 0.4%, and steady-state error of 0.47%, which are improvements over the PID controller. The use of SCADA Wonderware InTouch demonstrates a small delay time, namely 0.0920 ms for indicators, 0.0416 ms for monitoring value, and 0.1131 ms for input parameters, indicating efficient data management. Overall, the Sugeno fuzzy controller excels in all aspects and is highly suitable for application in the industry to maintain water temperature stability, achieve the desired temperature, and improve efficiency in nonlinear systems. Furthermore, SCADA support enables fast and accurate data monitoring and control.*

Keywords – *Fuzzy Logic Sugeno; PID Ziegler Nichols; SCADA; Water Control System; Wonderware InTouch.*

I. INTRODUCTION

INDUSTRIES such as chemicals, food, and beverages often require heating water to a certain temperature to ensure the quality, consistency, and efficiency of the process [1, 2]. However, this heating is often affected by external factors that cause the temperature to become unstable. Therefore, a temperature control system that can reach the setpoint quickly and accurately is highly needed. Unfortunately, many heating systems still use *on-off* control, which only has two conditions. This system is prone to instability and oscillation because it cannot adjust to existing disturbances [3, 4]. For that, more effective water temperature control is needed.

PID (Proportional-Integral-Derivative) is effective for linear systems with predictable input-output relationships that do not undergo significant changes [5, 6]. However, in nonlinear systems such as water heating processes, PID becomes less effective because fixed parameters cannot adjust to system dynamics such as delay time and varying heat capacity, which can cause slow response, overshoot, oscillation, or instability. Additionally, PID struggles to process qualitative information such as “temperature too high” or “approaching setpoint.”

As an alternative, fuzzy logic offers a more flexible solution because it does not rely on precise mathematical models, but rather uses rules based on fuzzy membership [7–10]. This approach is more suitable for nonlinear systems, as fuzzy logic uses membership values between 0 and 1 [3, 11, 12] to represent data that does not have strict boundaries in handling uncertainty [13–15].

The implementation of Supervisory Control and Data Acquisition (SCADA) in water temperature control systems offers an efficient solution for real-time monitoring, control, and data acquisition [16, 17]. By integrating sensors with PLC and smart devices connected to Microsoft Office CSV, the data acquisition process becomes fast and accurate. Wonderware InTouch SCADA visualization makes it easy for operators to monitor system conditions, allowing for effec-

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tive comparison between PID and fuzzy control methods, reducing downtime, and enhancing stability and productivity. This system reduces operational time, minimizes errors, and optimizes temperature control performance [18–20].

Previous research [10] on a Continuous Stirred-Tank Reactor (CSTR) shows that the use of fuzzy logic is more effective in reducing overshoot and error compared to the Ziegler-Nichols PID in Matlab Simulink simulations. Another study [21] concludes that fuzzy logic is more efficient than PID in a baby incubator using the DS18B20 sensor and Arduino for PWM control. While PID reduces temperature error, it causes oscillation, whereas fuzzy logic is more stable, faster, and without overshoot. The temperature is displayed on the Nextion TFT screen. Research [21] also shows that the Ziegler-Nichols method and its improvements on the OMRON CP1H PLC enhance the stability and optimization of water level control with PID, although water temperature control still experiences overshoot and instability. SCADA Wonderware InTouch effectively monitors the system without direct data logging. However, in the same study [22], the temperature control of the electric hot water tank (EHWT) shows that PID has an error of ±1°C and a stabilization time of 390 seconds. Fuzzy PID reduces the stabilization time by 43.1% and eliminates overshoot, while fuzzy control reduces the error to ±0.1°C, improving accuracy and stability using MATLAB/Simulink.

Although water temperature control using PID methods and fuzzy logic has been extensively researched on platforms such as ESP8266, Arduino, and MATLAB Simulink simulations, direct comparisons between PID methods with Ziegler-Nichols tuning and Sugeno fuzzy logic on industrial PLCs, specifically Omron CP1H, are still very limited. In addition, the application of SCADA systems using Wonderware InTouch for monitoring, control, and data acquisition in single-tank temperature control systems has not yet been widely implemented directly.

To fill the gaps in previous research, this study proposes the design of a temperature control system based on the Omron CP1H PLC by comparing two control methods, namely PID tuned using the Ziegler-Nichols method and fuzzy logic with the Sugeno approach, to identify the most effective control method in handling the nonlinear characteristics of the system, with a focus on minimizing errors, achieving stability, and responding quickly to setpoint changes in a single tank. This control system is integrated with SCADA Wonderware InTouch to support real-time monitoring and operational data logging. It is expected that the results of this research can be applied in industrial environments to improve process efficiency and product quality.

II. Research Methods

In this research, the approach used to achieve success is experimental. This approach is used to determine the cause-and-effect relationship [23], by applying certain treatments to the PID control method or fuzzy logic for the water heating process, then observing and analyzing the resulting system response. The sequence of steps includes conducting a literature review, system needs analysis, system design, PID control design, fuzzy logic control design, analysis results, comparing system results, and finally drawing conclusions. The research method is in the form of a flowchart that can be seen in Figure 1.

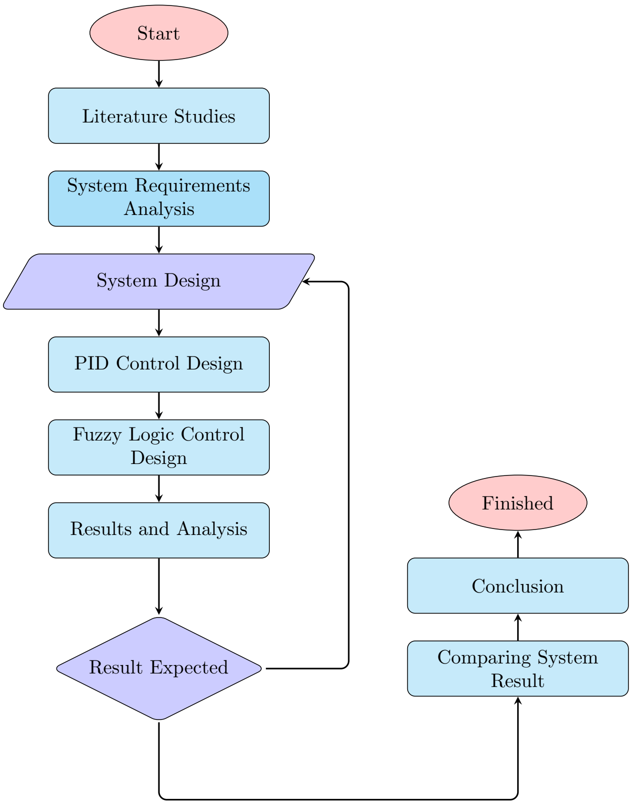


Figure 1: Research Methodology Flowchart

i. Literature Studies

The literature review phase is conducted by searching for and collecting previous research in the form of journals, datasheets, manuals, and reliable sources to find references, novelties, and supporting information for the research on the comparison of PID control methods with Fuzzy Logic in SCADA-based water temperature control.

ii. *System Requirements Analysis*

The author conducted a system needs analysis by identifying the components to be used in the water temperature control system, including actuators, controllers, communication protocols, sensors, and software for the SCADA interface, which are appropriately applied to support the research presented.

iii. *System Design*

In this study, the author discusses the comparison between the Ziegler-Nichols PID control method and Sugeno fuzzy logic based on SCADA. The SCADA used is Wonderware InTouch, which functions to monitor, control, and model the system. Modeling the system on SCADA means being able to record data integrated with CSV in Excel, and this recorded data can then be stored and used to model and analyze the system in MATLAB Simulink. To clarify the system that will be created, please refer to Figure 2.

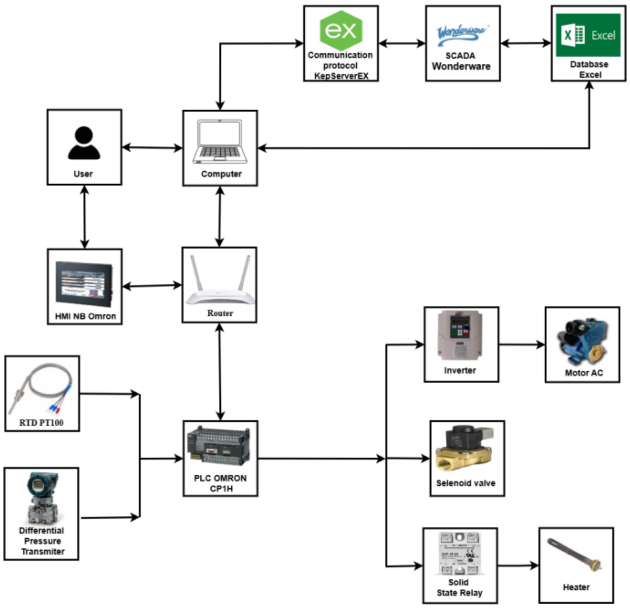


Figure 2: Overview of the System

The water temperature control system uses an Omron NB HMI connected wirelessly to an Omron CP1H PLC via a Wi-Fi router. Operators control and monitor the system through a laptop integrated with KEPServerEX as the communication protocol between the PLC and Wonderware InTouch SCADA. SCADA functions for monitoring, remote control, and real-time data logging to Microsoft Excel. The PLC receives data from an RTD PT100 sensor for temperature measurement and a Differential Pressure Transmitter for water flow pressure regulation. The actuators used include a solenoid valve to control water flow, an AC motor regulated through an inverter to pump water, and a heater controlled through a solid-state relay as needed for water temperature heating.

In this study, only one tank is used, namely tank 2, for the water temperature control system process, which will be visualized in the form of a P&ID, as shown in Figure 3. Tank 2 is used as a water container during the heating process. Where there is a sensor to measure the water level in the form of a DPT and inside the tank, there is an RTD PT-100 sensor as feedback. This information serves as a medium to control the inverter as the pump driver to regulate the flow rate of water entering the processing tank to maintain the water level and adjust the PWM duty cycle of the water heater according to the setpoint value. The system design using P&ID can be seen in Figure 3.

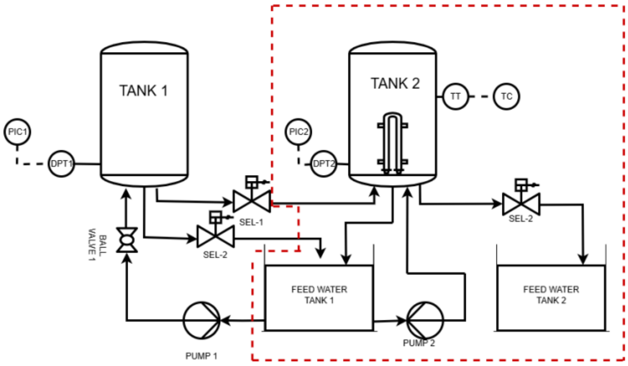


Figure 3: P&ID System Design

iv. *PID Control Design*

The control system design uses PID with parameter tuning based on the Ziegler-Nichols approach in a closed-loop configuration. The system operates based on error from the setpoint and actual temperature from the PT100 RTD sensor. The difference becomes PID input to regulate heater power until setpoint is reached.

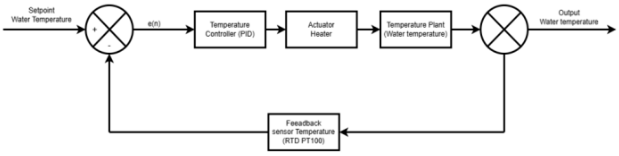


Figure 4: PID Control System Block Design

PID combines proportional (K_p), integral (K_i), and derivative (K_d) components. The tuning values used are $K_p = 3$, $K_i = 96$, and $K_d = 314$ based on Ziegler-Nichols [21].

v. *Fuzzy Logic Control Design*

The Sugeno fuzzy logic system operates in a closed-loop manner with two inputs: error $e(n)$ and delta error

$\Delta e(n)$. These are derived from the setpoint and actual temperature readings.

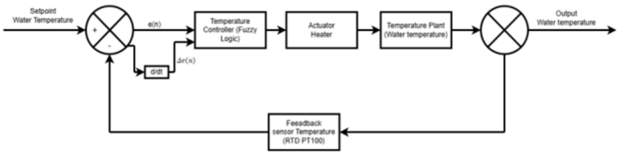


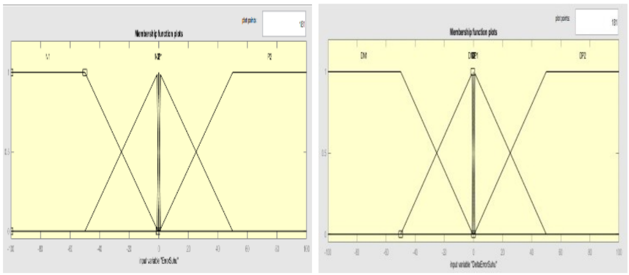
Figure 5: Fuzzy Logic Control System Block Design

$$e(n) = SP - \text{ASV} \tag{1}$$

$$\Delta e(n) = e(n) - e(n-1) \tag{2}$$

Where: $e(n)$ = current error $\Delta e(n)$ = error change SP = setpoint ASV = actual sensor value.

The fuzzification uses triangular and trapezoidal membership functions. Figure 6 shows the error and deltaError inputs.



(a) **(b)**

Figure 6: Fuzzy input design in MATLAB: (a) Membership error, (b) Membership DeltaError

The output PWM level is shown in Figure 7.

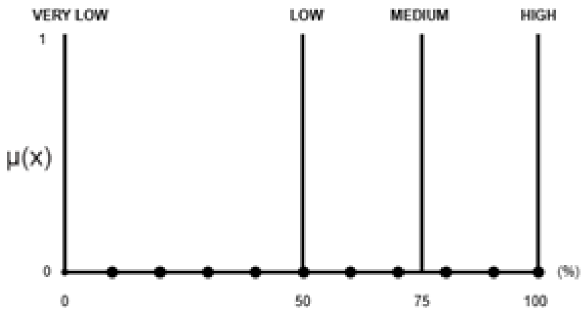


Figure 7: Design of Power Heater Output

The heater output is categorized as: VERY LOW (0), LOW (50), MEDIUM (75), HIGH (100).

The defuzzification uses the weighted average formula:

$$Z = \frac{\sum_{i=1}^{n} \alpha_i \cdot Z_i}{\sum_{i=1}^{n} \alpha_i} \tag{3}$$

Table 1: Sugeno Fuzzy Logic Rules

Error / Delta	DN1	DN2	DZ	DP1	DP2
N1	Very Low	Very Low	Very Low	Very Low	Low
N2	Very Low	Very Low	Very Low	Very Low	Low
Z	Very Low	Low	Very Low	Low	High
P1	Very Low	Low	Low	Low	Med
P2	High	High	Med	High	High

vi. Result and Analysis

This section analyzes the system behavior, stability, and efficiency based on test results.

vii. Comparing System Result

A comparison is made between the PID Ziegler-Nichols and Sugeno fuzzy logic results to evaluate which method is better for nonlinear water temperature control in terms of accuracy, stability, and speed.

III. RESULTS AND DISCUSSION

The result of the system design by merging each component, including actuators, controllers, and sensors, has been successfully integrated into a single water temperature system. The appearance of the device that has been created can be seen in Figure 8.

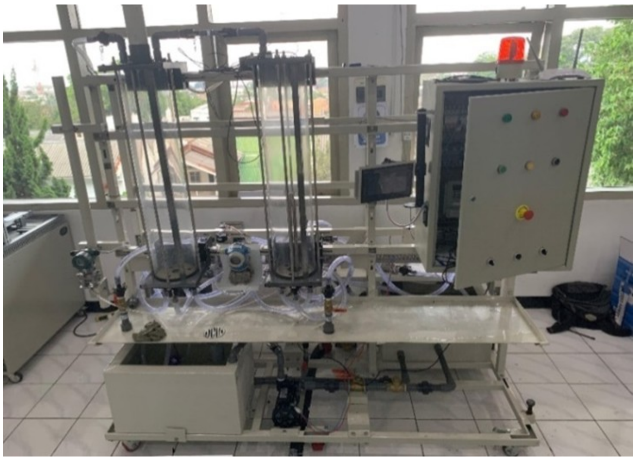


Figure 8: Water Temperature Control System

i. Results of PID Control Design

This study uses PID with the Ziegler-Nichols method, which from previous research yielded values of $K_p = 6$, $K_i = 96$, and $K_d = 24$. Based on these parameters, the system produced the following transient response:

1. Delay Time (Td): 121 seconds
2. Rise Time (Tr): 252 seconds
3. Settling Time (Ts): 12147 seconds
4. Maximum Overshoot (Mp): 1%
5. Steady-State Error (SSE): 0.37%

These results are used as a comparison basis against the Sugeno fuzzy logic system to evaluate performance in regulating water temperature.

ii. Results of the Sugeno Fuzzy Logic Control Design

The fuzzy logic control system is implemented using structured text within a function block diagram in the PLC. It consists of fuzzification, inference, and defuzzification stages. The system adjusts heater power via PWM based on the input error and delta error values.

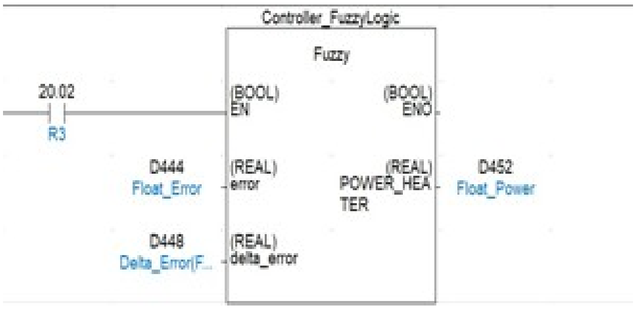


Figure 9: Function Block Fuzzy on PLC

To validate the accuracy and consistency of the fuzzy logic controller, a comparison is made between the MATLAB fuzzy logic toolbox output and the actual PLC output. The results are shown in Table 2.

Table 2: Comparison results of Power Heater

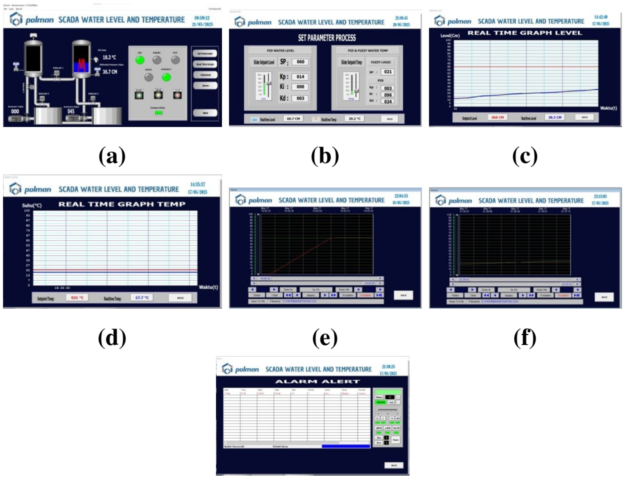
No	Input Error	Delta Error	MATLAB Power	PLC Power	Error Value (%)	Accuracy (%)
1	-27.0	60.0	50.00	50.00	0.00	100.00
2	33.2	-2.0	81.10	80.58	0.64	99.36
3	7.2	-0.2	58.00	61.65	6.29	93.71
4	55.0	60.0	100.00	100.00	0.00	100.00
5	-0.1	55.0	90.00	85.71	4.77	95.23
6	0.2	60.0	90.00	100.00	11.11	88.89
7	-8.0	-0.5	0.00	0.00	0.00	100.00
8	-0.5	-0.3	0.00	0.00	0.00	100.00
9	-6.0	0.2	0.00	0.00	0.00	100.00
10	0.4	-2.3	37.30	40.00	7.24	92.76
11	0.8	-0.2	50.40	50.74	0.67	99.33
12	20.0	1.0	70.00	74.99	7.13	92.87
13	25.0	2.5	75.70	74.99	0.94	99.06
14	36.8	3.5	86.80	75.00	13.59	86.41
15	11.2	-0.3	61.30	65.70	7.18	92.82
				Average	3.97	96.03

The comparison in Table 2 shows that the error between MATLAB and PLC output is relatively low, with an average error of 3.97% and accuracy of 96.03%. The differences are caused by rounding and algorithmic differences between MATLAB and the PLC's structured text execution. Nonetheless, the high accuracy confirms that the fuzzy logic controller is viable for real-world implementation in water temperature control.

iii. SCADA Monitoring, Controlling, and Modeling

The SCADA design results using Wonderware InTouch show effective monitoring functionality. SCADA displays real-time sensor and actuator values with graphical visualization. Alarm features provide warnings in case of abnormal system conditions.

The system enables direct control through a laptop via TCP/IP. A selector on the SCADA interface allows switching control methods during testing. The monitoring and control display can be seen in Figure 10.



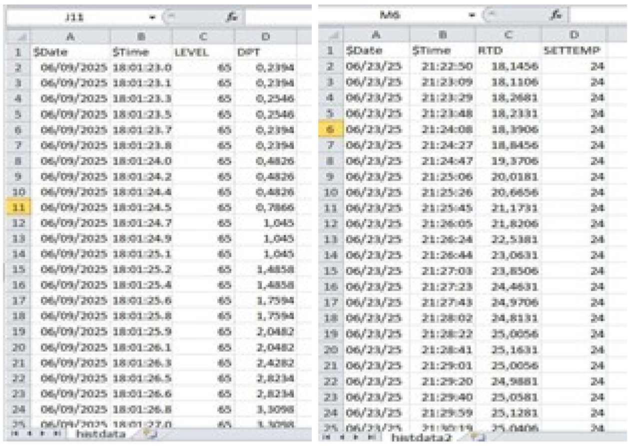
(a) (b) (c)

(d) (e) (f)

(g)

Figure 10: SCADA Wonderware InTouch

The SCADA modeling uses the data logging feature of Wonderware InTouch, recording level and temperature into CSV format for MATLAB Simulink modeling. The logging frequency is high, with 0.01–0.02 ms per data point.



	A	B	C	D
1	$Date	$Time	LEVEL	DPT
2	06/09/2025	18:01:23.0	65	0,2394
3	06/09/2025	18:01:23.1	65	0,2394
4	06/09/2025	18:01:23.3	65	0,2546
5	06/09/2025	18:01:23.5	65	0,2546
6	06/09/2025	18:01:23.7	65	0,2394
7	06/09/2025	18:01:23.8	65	0,2394
8	06/09/2025	18:01:24.0	65	0,4826
9	06/09/2025	18:01:24.2	65	0,4826
10	06/09/2025	18:01:24.4	65	0,4826
11	06/09/2025	18:01:24.5	65	0,7866
12	06/09/2025	18:01:24.7	65	1,045
13	06/09/2025	18:01:24.9	65	1,045
14	06/09/2025	18:01:25.1	65	1,045
15	06/09/2025	18:01:25.2	65	1,4858
16	06/09/2025	18:01:25.4	65	1,4858
17	06/09/2025	18:01:25.6	65	1,7594
18	06/09/2025	18:01:25.8	65	1,7594
19	06/09/2025	18:01:25.9	65	2,0482
20	06/09/2025	18:01:26.1	65	2,0482
21	06/09/2025	18:01:26.3	65	2,4282
22	06/09/2025	18:01:26.5	65	2,8234
23	06/09/2025	18:01:26.6	65	2,8234
24	06/09/2025	18:01:26.8	65	3,3098
25	06/09/2025	18:01:27.0	65	3,3098

	A	B	C	D
1	$Date	$Time	RTD	SETTEMP
2	06/23/25	21:22:50	18,1456	24
3	06/23/25	21:23:09	18,1106	24
4	06/23/25	21:23:29	18,2681	24
5	06/23/25	21:23:48	18,2331	24
6	06/23/25	21:24:08	18,3906	24
7	06/23/25	21:24:27	18,8456	24
8	06/23/25	21:24:47	19,3706	24
9	06/23/25	21:25:06	20,0181	24
10	06/23/25	21:25:26	20,6656	24
11	06/23/25	21:25:45	21,1731	24
12	06/23/25	21:26:05	21,8206	24
13	06/23/25	21:26:24	22,5381	24
14	06/23/25	21:26:44	23,0631	24
15	06/23/25	21:27:03	23,8506	24
16	06/23/25	21:27:23	24,4631	24
17	06/23/25	21:27:43	24,9706	24
18	06/23/25	21:28:02	24,8131	24
19	06/23/25	21:28:22	25,0056	24
20	06/23/25	21:28:41	25,1631	24
21	06/23/25	21:29:01	25,0056	24
22	06/23/25	21:29:20	24,9881	24
23	06/23/25	21:29:40	25,0581	24
24	06/23/25	21:29:59	25,1281	24
25	06/23/25	21:30:19	25,0406	24

(a) (b)

Figure 11: CSV Data Recording

Delay testing using Wireshark revealed:

1. Indicator: 0.0920 ms
2. Monitoring: 0.0416 ms
3. Input parameter: 0.1131 ms

Table 3: Delay Time Results

No	Testing	I/O	Average Delay (ms)
1	Indicator (Green Lamp, CIO 0100.00)	Output	0.0920
2	Monitoring (DPT D513)	Output	0.0416
3	Input Parameter (Set Temp D0)	Input	0.1131

iv. Results and Analysis

The system was tested using a setpoint of 24°C, water height of 60 cm, and initial temperature of 18.5°C. Control methods tested were PID Ziegler-Nichols and Fuzzy Logic Sugeno, as shown in Table 4.

Table 4: Comparison of Control Methods

No	Method	Setpoint ()	P	I	D
1	PID Ziegler-Nichols	24	6	96	24
2	Fuzzy Logic Sugeno	24	-	-	-

System response for each method is shown in Figures 12 and 13.

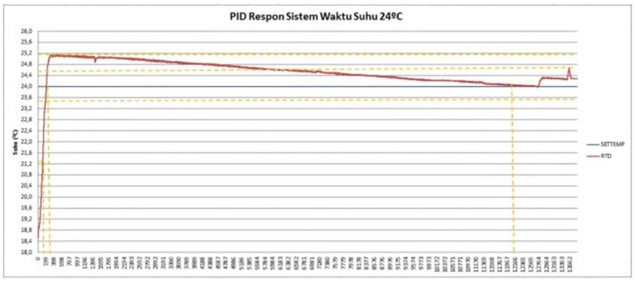


Figure 12: PID Z-N Transient System Response

PID results: Td = 121 s, Tr = 252 s, Ts = 12147 s, Mp = 1%, SSE = 0.37%. The system overshoots to 25.1°C before stabilizing at 24°C. With constant 50% PWM, reactivation occurs with a 3% rise when temperature drops slightly.

Fuzzy results: Td = 113 s, Tr = 226 s, Ts = 6587 s, Mp = 0.6%, SSE = 0.03%. This method showed quicker setpoint achievement, lower overshoot, and more stable temperature maintenance due to dynamic PWM output adjustment.

v. Comparing System Results

Table 5 presents the performance comparison between the two control methods.

The Sugeno fuzzy logic controller is more efficient. It shortens delay by 8 s, rise time by 26 s, and cuts settling time nearly in half. With a 0.6% overshoot and 0.03% SSE, the fuzzy controller achieves faster and more accurate temperature regulation.

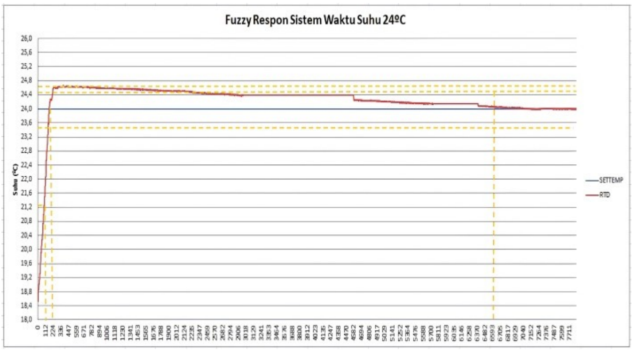


Figure 13: Response of the Sugeno Fuzzy Logic Transient System

Table 5: Comparison Results of System Response

Method	Td (s)	Tr (s)	Ts (s)	Mp (%)	SSE (%)
PID Ziegler-Nichols	121	252	12147	1.00	0.37
Fuzzy Logic Sugeno	113	226	6587	0.60	0.03

IV. CONCLUSION

This research presents a SCADA-based water temperature control system using PID and fuzzy logic controllers. The objective was to determine the most suitable control method by evaluating system responses under both approaches. The results demonstrate that the fuzzy logic controller significantly outperforms the PID controller in key performance metrics such as delay time, rise time, settling time, maximum overshoot, and overall system stability. Specifically, the fuzzy controller achieved a low overshoot of just 0.6°C and faster convergence to the setpoint, indicating its superior ability to handle the nonlinear behavior of the tested system. Therefore, the fuzzy logic controller is more effective and reliable for maintaining stable water temperatures in dynamic and nonlinear environments, making it a highly suitable choice for industrial applications requiring precise thermal control.

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