Implementation of adaptive PID control for maintaining temperature stability during steady-state conditions in stirred heating tank

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ABSTRACT

Temperature stability is a crucial factor in industries such as chemicals, pharmaceuticals, and food processing, where fluctuations can damage product quality and increase energy consumption. This study aims to optimize heater power control using an adaptive proportional integral derivative (PID) control system to maintain temperature stability under steady-state conditions. The method involves applying adaptive PID control to a stirred heating tank using LabVIEW software with a national instruments controller module and a single-phase SCR to regulate heater power and adjust control parameters in real time. The results indicate that the system operates more effectively under stable conditions, with faster response times and a lower overshoot of less than 0.12%. However, under disturbed conditions, such as water drainage and replacement, the system requires more time to adjust the temperature and experiences increased energy consumption and heat loss. Despite this, the system still achieves an energy efficiency improvement, with efficiency values ranging from 77.66% to 80.03%. The implementation of adaptive PID control demonstrates significant potential in enhancing system accuracy and response to temperature changes, contributing to the development of more efficient industrial control technologies.

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1. INTRODUCTION

Temperature stability is crucial in industries such as chemicals, pharmaceuticals, food, and energy, as unstable temperatures can degrade product quality, damage equipment, and lead to energy waste [1]. A reliable temperature control system is essential to maintain the desired temperature with a fast and accurate response to load changes or disturbances. Proportional integral derivative (PID)-based temperature control has been shown to provide higher accuracy and stability than conventional (on-off methods) [2]. Its practicality and effectiveness have been validated across different heating and cooling applications [3]. While conventional PID control can regulate heating power to maintain a set point, it often struggles to handle system nonlinearity and disturbances effectively [4], [5]. In contrast, adaptive PID control can adjust its parameters in real time based on changing system conditions, resulting in better performance compared to conventional PID [6]-[9]. By using an adaptive algorithm, the system automatically optimizes heating power to maintain the temperature at the set point, even in the presence of disturbances or variations in the thermal characteristics of the tank [10]-[12]. Although conventional PID control is commonly used in this system, it has limitations in handling changes in system parameters [13], [14]. To address these limitations, the adaptive PID method has been developed, allowing PID parameters (k_p, k_i, k_d) to be dynamically adjusted based on changing system conditions [15]-[18].

In the stirred heating tank system, the adaptive PID approach can handle temperature fluctuations caused by the addition or removal of water under steady-state [19], [20]. Research shows that using adaptive PID in stirred tank heater systems can reduce temperature fluctuations by up to 30% compared to conventional methods, especially during disturbances like the addition or removal of fluid [21], [22]. Furthermore, studies [18], [23] explain that applying adaptive PID controllers to stirred tank heaters improves response to temperature changes and disturbances, enhancing stability and control efficiency. The result [24]-[26] also indicates that the adaptive PID system in stirred tank heaters achieves high accuracy and efficiency in determining heat flux, making it effective in temperature control in response to system condition changes. Despite the progress made, gaps remain, such as optimizing adaptive algorithms for systems with unpredictable dynamic disturbances and exploring more complex adaptive algorithms to manage dynamic disturbances in thermal systems [22], [27]-[29].

This study aims to optimize heater power control with adaptive PID to maintain steady-state stability, improve response to disturbances, enhance energy efficiency, and minimize overshoot and adjustment time. The stirred tank heater system can be modeled as a continuous stirred tank with inlet and outlet flows [19], [21], [27], [30]. In power electronics and drive systems (PEDS), effective thermal management is essential for ensuring device performance and longevity. It requires the capability to reach a target temperature with low overshoot and to reject disturbances rapidly. This experimental study employs a stirred-water loop with valve-induced inflow disturbances and focuses on PID-based heater power control to assess the system's capability to maintain temperature stability. The results provide practical insights for thermal-control design in PEDS applications. In this way, the system is expected to provide more accurate and stable temperature control in industrial applications, as well as improve performance and operational efficiency in heating systems.

2. METHOD

2.1. Experimental set-up

This study uses a 120 L stirred heating tank with an inlet expansion tank and LabVIEW-based adaptive PID control, insulated by 1-inch glass wool and aluminum foil (Figure 1). A 150 W agitator ensures water homogenization, enabling accurate readings from 12 K-type thermocouples. Meanwhile, a 25 L expansion tank with a solenoid valve regulates 10 L flow every 5 minutes to maintain 26.6 – 27.5 °C.

Simultaneously, the system drains 10 L of water to keep the total volume at 120 L, as shown in Figure 2. Temperature control is achieved by comparing the measured temperature with the set point, which ranges from 50 °C to 95 °C. The error (or difference) is calculated and processed by the adaptive PID system, which then determines the control parameters k_p, k_i, and k_d. The PID system output is converted into a digital signal, which controls the power of four heaters through a National Instruments power control module. A silicon-controlled rectifier (SCR) ensures that sufficient power is supplied to maintain the set point temperature.

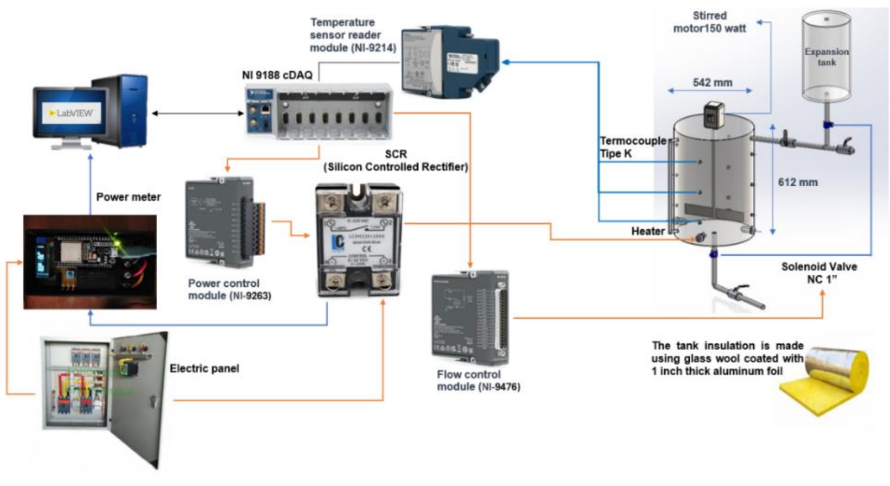


Figure 1. Adaptive control system test setup

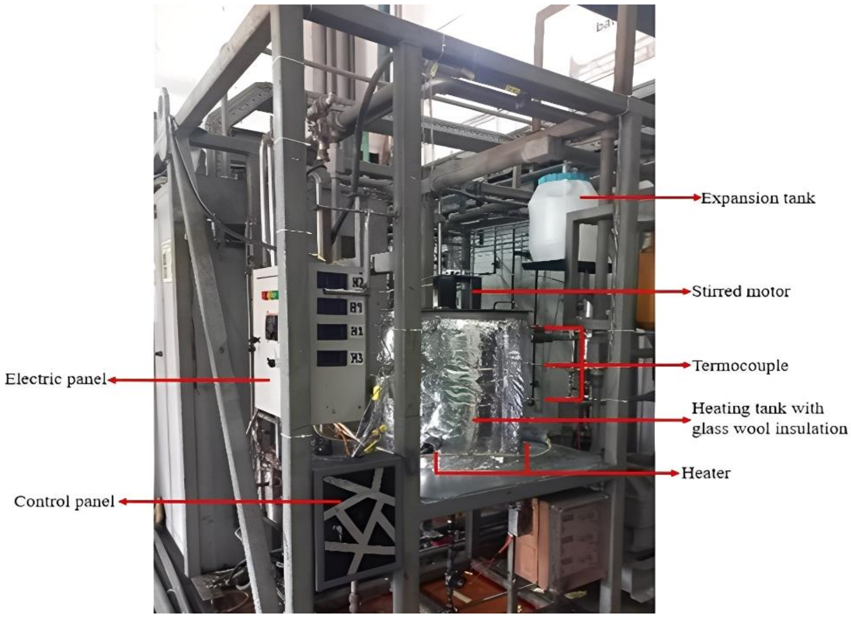
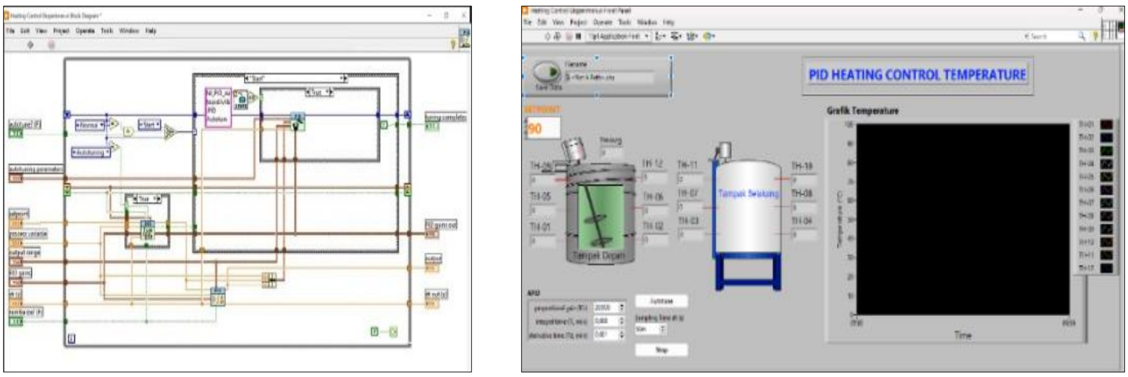


Figure 2. Experimental facility



(a) (b)

Figure 3. PID adaptive control system program: (a) wiring block diagram and (b) front panel

2.2. PID controller modelling

In LabVIEW, the PID control is enhanced with adaptive control using the gain scheduling toolkit within the PID toolkit. The autotuning feature is used to determine the optimal PID parameters initially, while the adaptive control automatically adjusts the PID parameters during the experiment to maintain system stability, even in the presence of external disturbances, as shown in Figure 3. The mathematical model for conventional PID control is as (1):

$$u(t) = K_p e(t) + K_i \int_0^t e(t)d(t) + K_d \frac{de(t)}{d(t)} \tag{1}$$

Where:

$$K_i = \frac{K_p}{T_i} \tag{2}$$

$$K_d = K_p \cdot T_d \tag{3}$$

The adaptive PID control system, enhanced with adaptive control logic, uses the gain scheduling method to update the parameters Kp, Ki, and Kd as follows:

$$K_p(t+1) = K_p(t) + \alpha_p e(t) e(t-1) \tag{4}$$

$$K_i(t+1) = K_i(t) + \alpha_i e(t) \int_0^t e(t)\, dt \tag{5}$$

$$K_d(t+1) = K_d(t) + \alpha_d e(t) \frac{de(t)}{dt} \tag{6}$$

Where α_d, α_i, and α_p are the adaptation factors in the adaptive control logic. Based on these equations, the mathematical model of the Adaptive PID control system becomes:

$$u(t) = K_p(t)e(t) + K_i(t) \int_0^t e(t)d(t) + K_d(t) \frac{de(t)}{d(t)} \tag{8}$$

$$u(t) = K_p(t)e(t) + K_i(t) \sum_{i=0}^{t} e(i)\Delta t + K_d(t) \frac{e(t)-e(t-1)}{\Delta(t)} \tag{9}$$

Based on Figure 3, the gain scheduling method in adaptive control dynamically adjusts the control parameters, ensuring system stability, even in the presence of disturbances. The LabVIEW-based adaptive PID system uses primary PID tools and a solenoid valve control schematic, with a front panel for real-time parameter and temperature monitoring to ensure usability and effective visualization. The setup uses a heated water tank, K-type thermocouples, NI 9214 for temperature acquisition, NI 9263 for SCR phase control, and real-time parameter tuning in LabVIEW. Gain scheduling is chosen for its real-time parameter adjustment, minimizing overshoot while maintaining fast response, offering simpler and more robust control than fuzzy logic or neural networks. The thermal model applies energy balance for conduction, convection, and radiation, showing disturbance effects and highlighting SCR-based power control for improved resolution and efficiency [31].

3. RESULTS AND DISCUSSION

3.1. Temperature control system response

Increasing set points cause adaptive PID parameters to require greater control effort, with higher power and stronger adjustments needed to reach and stabilize temperatures. Consequently, the P, I, and D parameters increase to correct errors, respond to temperature changes, and minimize rapid fluctuations, keeping overshoot within limits. Table 1 shows that adaptive PID parameters are smaller without disturbances, while disturbances require faster responses, leading to larger parameters to maintain stability.

Table 1. Adaptive PID parameters from the experimental results and characteristics parameters of temperature with disturbance

Temperature Set Point (°C)	Parameter APID with Disturbances			Parameter APID without Disturbances			Rise Time (seconds)	Overshoot (%)	Low Point (°C)	Back to steady (second)
	k_p	k_i	k_d	k_p	k_i	k_d				
50	22.84	1.12	3.91	20.52	1.11	2.12	628	0,04	46.4	201
55	24.26	1.60	3.71	21.73	1.25	2.16	820	0.14	51.0	248
60	23.22	1.29	3.22	21.91	1.14	2.46	997	0.26	56.3	196
65	24.43	1.60	4.12	22.29	1.42	2.23	1129	0.05	61.1	273
70	25.93	1.41	4.41	22.15	1.19	2.38	1266	0.06	66.9	198
75	26.81	1.71	3.87	22.47	1.59	2.15	1387	0.16	71.28	149
80	27.11	2.28	3.65	22.53	1.86	2.53	1489	0.18	77.4	147
85	28.81	1.91	4.29	23.09	1.73	2.84	1513	0.02	82.8	132
90	29.26	2.49	4.38	23.78	1.90	2.71	1782	0.15	87.9	126
95	28.94	2.54	4.52	23.41	1.87	2.98	1931	0.07	93.0	119

Figure 4 shows that the overshoot is smaller without disturbances. This occurs because the adaptive PID control accelerates the system's adjustment. In the disturbed experiment, the PID system has not fully adapted, resulting in an excessive initial response and a larger overshoot. In contrast, in the undisturbed experiment, the system benefits from data memory, allowing adaptive control to respond more accurately and minimize errors. Figure 5 shows that the steady-state error is larger in disturbed experiments due to rapid temperature changes that hinder accurate adaptive PID power adjustment. For instance, when colder water replaces drained water, the system becomes unstable. The varying heat demand makes it difficult to maintain the set point temperature. When the adaptive PID fails to adjust parameters, heater output is not fully utilized, making it harder to reach the set point and increasing steady-state error.

Temperature change remains stable and controlled as the adaptive PID reduces heater power near the set point, stabilizing water temperature before it is reached. The heating process begins with a rapid increase. As shown in Figures 4 and 5, the adaptive PID reduces heater power near a set point to slow temperature rise, enabling precise evaluation and preventing overshoot. Figure 4 illustrates rapid temperature responses at various set points, with non-uniform disturbances and reliable recovery. Higher set points recover faster but take longer to reach, indicating control imbalance and the need for adaptive improvements (Table 1). Although shorter rise times could increase overshoot, it remained below 0.26% for all set points, with water drainage and addition during the first hour causing a 3.6 °C drop at the 50 °C set point under 2-hour steady-state conditions. The system required 201 seconds to restore the temperature to the set point value.

Figure 6 shows the Adaptive PID holding temperature before the set point to enhance stability and prevent overshoot by dissipating residual heat. Based on Table 2, higher set points significantly increase rise time, showing greater energy demand and revealing heater efficiency or control limitations at elevated temperatures. Overshoot stays low across all temperatures but peaks nonlinearly at mid-range, with the highest value of 0.12% at 65 °C. In contrast, at a higher temperature, such as 90 °C, the overshoot is much lower (0.02%). This pattern indicates that, despite effective control, nonlinear factors affect thermal response, yet the system still operates with stable performance.

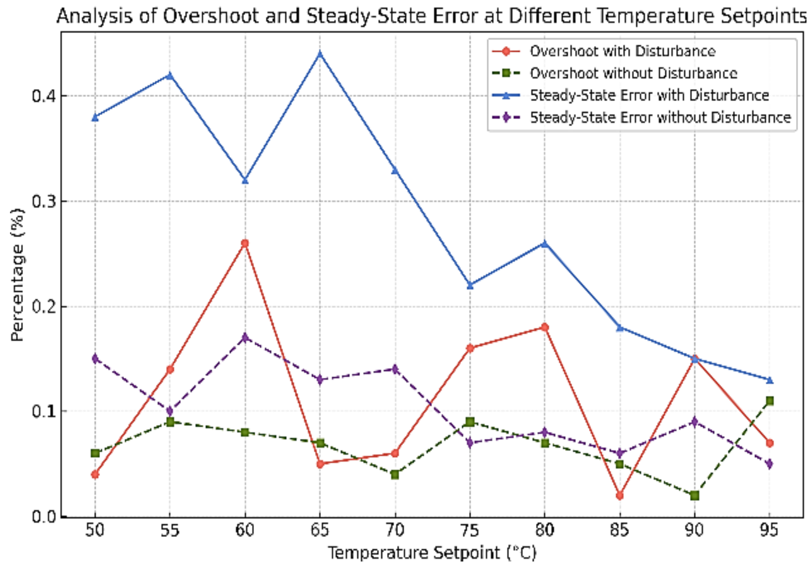


Figure 4. Overshoot and error steady-state profiles

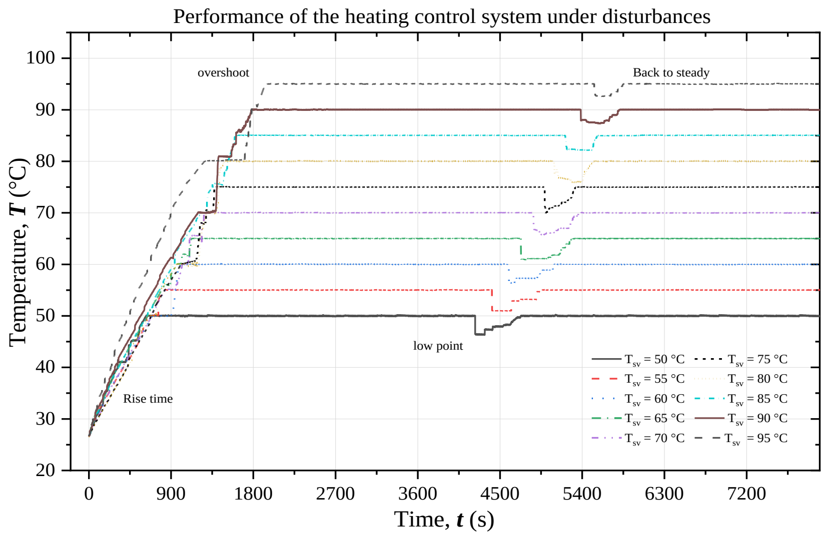


Figure 5. Characteristics of temperature with disturbance

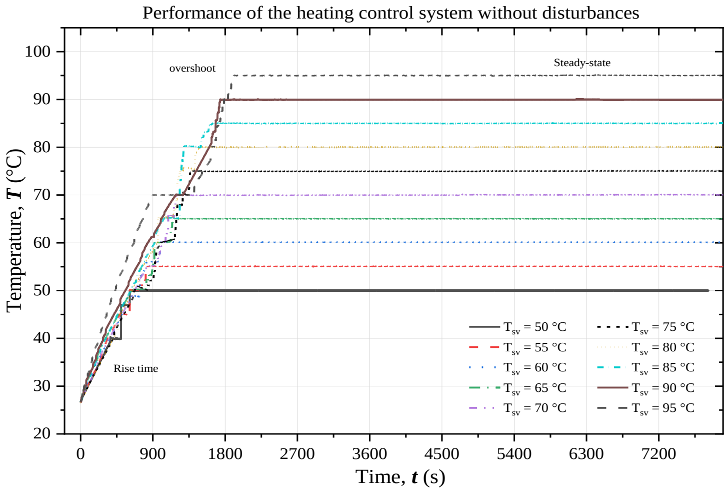


Figure 6. Characteristics of temperature without disturbance

Table 2. Temperature profiles without disturbance

Temperature set point (°C)	Rise time (seconds)	Overshoot (%)	Temperature set point (°C)	Rise time (seconds)	Overshoot (%)
50	613	0,06	75	1367	0.09
55	832	0.09	80	1493	0.07
60	989	0.08	85	1641	0.05
65	1152	0.12	90	1739	0.02
70	1195	0.04	95	1908	0.11

3.2. Heat absorption analysis

The adaptive PID control adjusts parameters to reach the set point, causing power fluctuations while water temperature stabilizes gradually during transients. In steady state, heater power stabilizes as the system reaches equilibrium, with fewer heaters active at lower set points, as shown in Figure 7. To maintain the set point temperature, the adaptive PID system typically activates two or three heaters in response to disturbances. Even with disturbances, steady-state heat loss is minimal, yielding constant water temperature and stable power, while transients force heaters to work harder with greater loss.

Figure 7 shows power fluctuations with sharp variations as the heater responds to temperature changes, remaining stable at lower temperatures but increasing notably at 90 °C and 95 °C. This pattern shows disturbance effects, where the heater adjusts power to maintain the set point, with adaptive PID increasing power and switching off more heaters at higher set points. The system turns off all four heaters to maintain stability up to 80 °C, but only two heaters are turned off at 85 °C and 95 °C set points.

Figure 8 shows heater power profiles without disturbances, where power is more stable with smoother fluctuations and remains low at 50–55 °C. As the set point rises from 70 °C to 95 °C, power usage increases with slight fluctuations to maintain the temperature at the set point. Average power requirements for each set point can be analyzed from steady-state heater patterns without disturbances. Water discharge disturbances cause heat fluctuations, requiring extra power to reheat incoming replacement water.

This effect is reflected in the higher values of $q_{electric}$ and q_{loss} compared to the results from the undisturbed experiments, particularly at higher temperatures, as shown in Figures 9 and 10. Based on Figure 9, the values of $q_{electric}$ and q_{absorb} increase with the rise in set point temperature. The system efficiency ranges from 77.21% to 80.09%, with the highest value of 80.09% achieved at 80 °C. Despite higher heat loss at elevated temperatures, system efficiency remains stable and is optimal around 80 °C. This indicates the heating system effectively converts electrical energy into heat, though efficiency drops slightly to 79.82% at 85–95 °C due to increased heat loss and reduced performance.

Figure 10 shows that electric power ($q_{electric}$) and heat loss (q_{loss}) show a sharp increasing trend. Efficiency slightly decreases with rising set point temperature, remaining around 79%. Higher temperatures demand more power and generate greater loss, though efficiency is not significantly affected. Increased energy consumption and higher heat loss in the disturbed experiment result from water discharge disrupting thermal stability in the heating tank. System efficiency in the disturbed experiment is lower and more fluctuating, indicating a more optimal operation under undisturbed conditions without energy loss from water replacement. Water discharge disturbances increase electrical energy consumption and heat loss while reducing system efficiency, highlighting the importance of steady-state stability. In the undisturbed experiment, the system maintains higher efficiency with lower energy consumption.

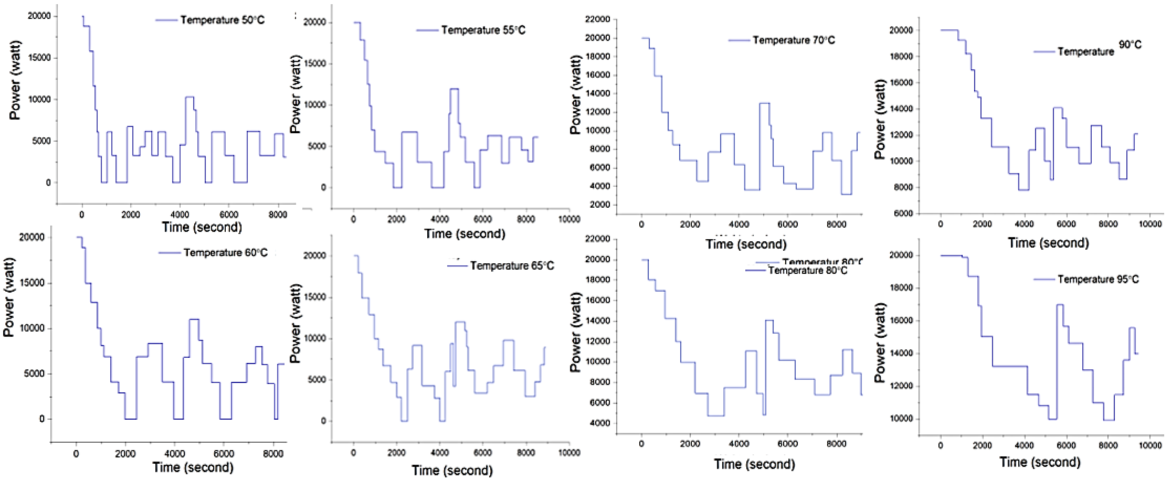


Figure 7. Characteristics of heater power with disturbance

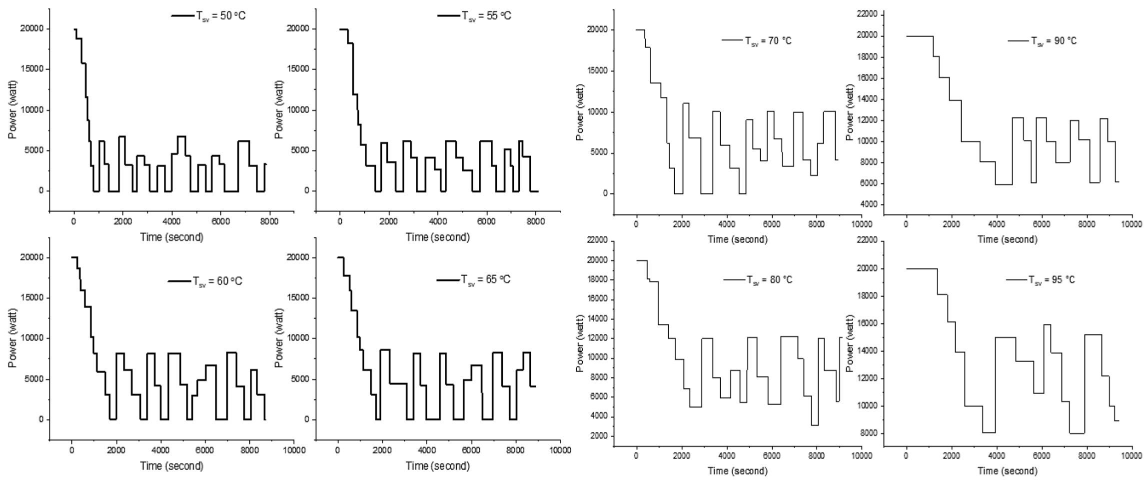


Figure 8. Characteristics of heater power without disturbance

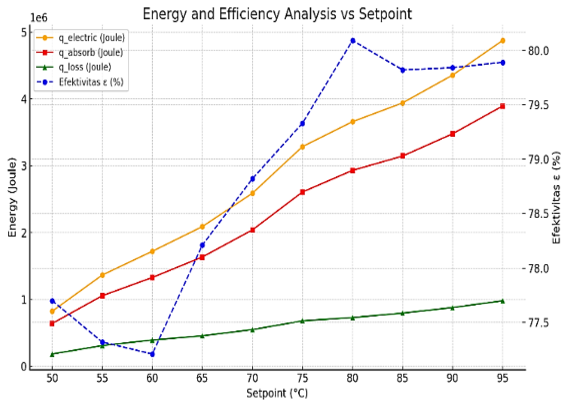


Figure 9. Heat absorption with disturbance

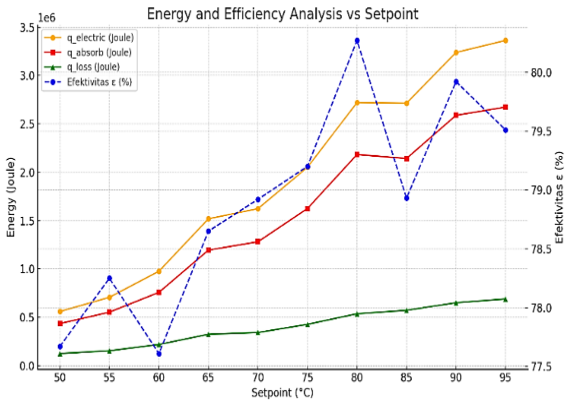


Figure 10. Heat absorption without disturbance

4. CONCLUSION

Under disturbed conditions, Adaptive PID parameters increase for faster adjustment, but steady-state error grows as the controller takes longer to regulate heating power. In the undisturbed experiment, the rise time was approximately 25 seconds faster, with an overshoot of less than 0.12%, whereas in the disturbed experiment, the overshoot reached 0.26%. Heat absorption and loss analysis showed higher energy use and heat loss in disturbed experiments, especially at higher set points, as the system worked harder to maintain stability. Although efficiency peaked at 80 °C, disturbances reduced it at higher temperatures with greater heat loss, highlighting the need for steady-state stability to optimize performance.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Agus Sunjarianto Pamitran	✓			✓			✓			✓		✓	✓	✓
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Mulya Juarsa		✓								✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

DATA AVAILABILITY

The data supporting the findings of this study are available upon request from the corresponding author, [MJ]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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