International Journal of Sustainable Social Culture, Science Technology, Management, and Law Humanities, 3(1), (2026)

Design And Implementation Of An Embedded Temperature Control System For Laboratory-Scale Pyrolysis Applications

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Article history
Received: 21 May 2026
Revised: 18 June 2026
Accepted: 29 June 2026

Keywords
Embedded System;
Temperature Control;
Laboratory-Scale Pyrolysis;
On–Off Control

Abstract
Accurate and stable temperature control is essential in laboratory-scale thermal processing, as it directly influences process stability, operational safety, and experimental reproducibility. However, many laboratory thermal systems still rely on manual regulation or simple heating mechanisms without adequate feedback control, resulting in temperature fluctuations and inconsistent performance. This study presents the design and implementation of an embedded temperature control system for laboratory-scale thermal processing, using pyrolysis as an application case study. The proposed system is based on a closed-loop control architecture that integrates a K-type thermocouple, a microcontroller-based control unit, and an electrical heating actuator. A hysteresis-based on–off control strategy is implemented to regulate the heating process and maintain the desired temperature setpoints. The system performance is experimentally evaluated at operating temperatures of 300 °C, 400 °C, and 500 °C under different processing durations. Experimental results demonstrate that the developed system provides stable and reliable temperature regulation across all tested conditions. The system exhibits a rapid heating response, minimal overshoot, and acceptable steady-state temperature deviations, even at elevated operating temperatures. Long-duration operation confirms the robustness and reliability of the control strategy. These results indicate that the proposed embedded temperature control system offers a practical and cost-effective solution for laboratory-scale thermal processing applications requiring stable and repeatable temperature control.

1. Introduction

Temperature control is a fundamental requirement in thermal processing systems, as it directly affects process stability, operational safety, and result reproducibility [1],[2]. In laboratory-scale thermal applications, inaccurate or unstable temperature regulation often leads to inconsistent system behavior, reduced process efficiency, and unreliable experimental outcomes [3],[4], [5]. Therefore, the development of an automatic and reliable temperature control mechanism is a critical design consideration in the construction of laboratory-scale thermal processing equipment. Many existing laboratory-scale thermal systems still rely on manual temperature adjustment or basic heating mechanisms without closed-loop feedback [6]. Such approaches are highly dependent on operator intervention and are prone to temperature overshoot, delayed response, and instability during operation [7]. These limitations not only compromise process performance but also introduce safety risks and restrict the scalability and repeatability of the system [1], [8],[9]. Moreover, the absence of an integrated control framework limits opportunities for systematic performance evaluation and future technological enhancement.

Recent advancements in embedded systems have enabled the implementation of compact, flexible, and cost-effective solutions for real-time monitoring and control applications [10]. Microcontroller-based embedded platforms, when integrated with temperature sensors and actuator control units, allow automatic regulation of heating elements through feedback-based control strategies [11]. This integration significantly improves temperature stability, enhances operational safety, and ensures consistent system performance. Furthermore, embedded control systems provide a solid foundation for future extensions toward intelligent control, data acquisition, and network-based monitoring [11],[12]. Pyrolysis is a thermal processing application that requires stable and well-regulated temperature conditions to ensure reliable operation [13], [14],[15]. Although numerous studies have investigated pyrolysis in terms of material conversion efficiency and product yield, relatively limited attention has been given to the implementation and evaluation of embedded temperature control systems that support the stability and reliability of the pyrolysis process itself, particularly at the laboratory scale [7],[10],[11].

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doi: https://doi.org/10.71131/qbvtmd78

In many reported systems, temperature control is treated as a secondary component, with minimal discussion of control architecture, system integration, and control performance [12], [16].

In response to this research gap, this study focuses on the design and implementation of an automatic temperature control system based on an embedded microcontroller platform for a laboratory-scale pyrolysis prototype. The proposed system integrates a temperature sensing unit, a microcontroller-based control unit, and an actuator mechanism to regulate the heating process through closed-loop control. The system is implemented as a complete hardware–software solution and evaluated under various operating temperatures and processing times, with the pyrolysis process employed as an application case study. The primary contribution of this work lies in the practical realization and performance evaluation of an embedded temperature control system for laboratory-scale thermal processing applications. Unlike previous studies that primarily emphasize pyrolysis outcomes, this research highlights system architecture, control implementation, and temperature stability as the main focus. The results of this study are expected to contribute to the development of applied embedded control systems and provide a reference framework for designing automated, temperature-controlled thermal processing equipment.

2. Method

This study adopts an applied research methodology focusing on the design, implementation, and performance evaluation of an embedded temperature control system for a laboratory-scale thermal processing unit. The methodology is structured to emphasize system architecture, hardware–software integration, control strategy implementation, and quantitative performance evaluation. Pyrolysis operation is employed as an application case study to demonstrate the effectiveness and reliability of the proposed temperature control system under real operating conditions.

2.1. Overall System Architecture

The overall architecture of the proposed system is illustrated in Fig. 1. The system is designed as a closed-loop embedded temperature control system, in which real-time temperature feedback is continuously monitored and processed to regulate the heating process automatically. The architecture consists of four main subsystems: a temperature sensing unit, a microcontroller-based control unit, an actuator unit, and a thermal processing unit.

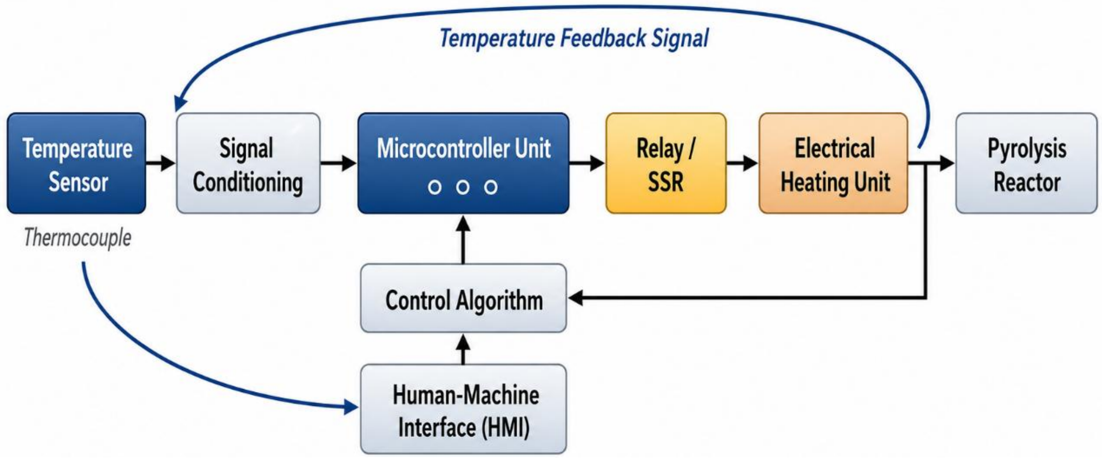

Fig. 1. Block diagram of the embedded temperature control system

The temperature sensing unit measures the reactor temperature and transmits the feedback signal to the control unit. The microcontroller processes this input using a temperature control algorithm and generates a corresponding control signal for the actuator unit. The actuator regulates the electrical power supplied to the heating unit, allowing the system to maintain the desired temperature setpoint. This closed-loop configuration ensures stable temperature regulation, improves operational safety, and enhances overall system reliability.

2.2. Hardware Design

The hardware configuration of the embedded temperature control system consists of interconnected components that enable sensing, processing, actuation, and user interaction. A high-temperature K-type thermocouple is used to measure the reactor temperature accurately under elevated thermal conditions. The thermocouple output is conditioned using a dedicated signal conditioning module before being transmitted to the microcontroller unit. The microcontroller serves as the central processing and control unit, responsible for executing the temperature control algorithm and managing system operation. An actuator interface, implemented using a relay or solid-state relay (SSR), controls the electrical power supplied to the heating unit based on the control signal generated by the microcontroller. A human–machine interface (HMI) module is integrated to display real-time temperature data and system status information. The detailed hardware components and their respective functions are summarized in Table 1.

Table 1. hardware components of the embedded temperature control system

Component	Type / Model	Function
Temperature Sensor	K-type thermocouple	Measures reactor temperature in real time
Signal Conditioning Module	Thermocouple amplifier	Converts sensor signal to readable data
Microcontroller Unit	Arduino / ESP32	Processes data and executes control algorithm
Actuator Interface	Solid State Relay	Controls power supplied to the heater
Heating Element	Electrical heater	Generates thermal energy
Display Module	LCD / OLED	Displays temperature and system status
Power Supply	AC–DC converter	Supplies electrical power to the system

All hardware components are assembled into an integrated prototype with appropriate electrical insulation and thermal protection to ensure safe and reliable operation during high-temperature thermal processing.

2.3. Software and Temperature Control Algorithm

The software system is implemented on the microcontroller platform and operates in real time to regulate the temperature of the thermal processing unit. The control logic is based on a closed-loop on–off feedback control strategy combined with a predefined hysteresis band. The hysteresis mechanism is introduced to prevent excessive actuator switching and to reduce temperature oscillations around the desired setpoint.

The flowchart of the temperature control algorithm is presented in Fig. 2. The control process begins with system initialization, followed by continuous acquisition of temperature data from the sensor. The measured temperature is compared with the predefined temperature setpoint range, which consists of lower and upper threshold limits. If the measured temperature falls below the lower limit, the heating unit is activated. Conversely, if the temperature exceeds the upper limit, the heating unit is deactivated. When the temperature remains within the hysteresis range, the current actuator state is maintained to ensure stable operation.

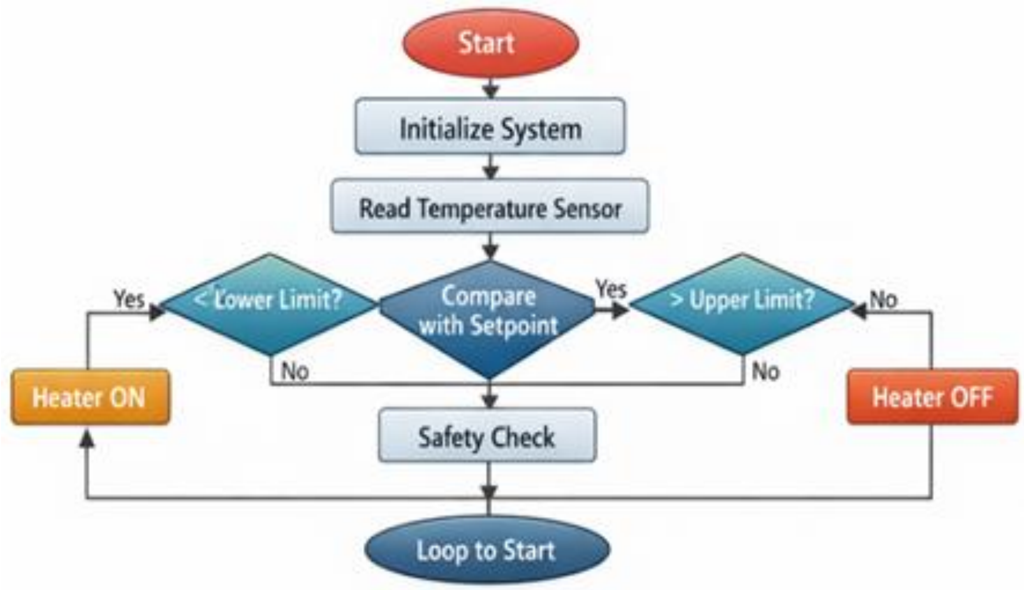

Fig. 2. Flowchart of the temperature control algorithm

A safety check is performed during each control cycle to detect abnormal operating conditions, such as excessive temperature rise or sensor malfunction. The control loop operates continuously throughout system operation, enabling real-time temperature regulation and consistent system performance.

2.4. System Integration and Prototype Implementation

System integration involves combining the hardware and software components into a unified embedded temperature control system. The temperature sensor, microcontroller unit, actuator interface, heating unit, and HMI are interconnected according to the designed system architecture. Communication between components is verified to ensure accurate data transmission and reliable actuator response.

Fig. 3. Integrated prototype of the temperature control system

The integrated prototype of the temperature control system is shown in Fig. 3. The prototype demonstrates the physical realization of the designed system and confirms that the embedded control architecture can be implemented effectively in a laboratory-scale thermal processing environment.

2.5. Experimental Setup and Evaluation Method

The performance of the proposed temperature control system is evaluated through experimental testing using a laboratory-scale thermal processing setup. The system is tested at various temperature setpoints (300°C, 400°C, and 500°C) and processing durations 15 minutes to assess temperature stability and control response. The experimental parameters used in the evaluation are summarized in Table 2.

Tabel 2. Experimental Parameters For System Evaluation

Parameter	Value
Temperature setpoints	300°C, 400°C, 500°C
Processing time	15 minutes
Control method	On–off temperature control
Sensor sampling rate	Real-time measurement
Heating source	Electrical heating element
Evaluation criteria	Temperature stability and control response

During each experiment, temperature data are recorded continuously to observe system behavior over time. Pyrolysis operation is used as an application case study to validate the effectiveness of the control system under real thermal processing conditions.

3. Result and Discussion

3.1. Temperature Control Performance

Fig. 4 presents the temperature–time responses of the embedded control system at operating setpoints of 300°C, 400°C, and 500°C. The results reveal a consistent control behavior across all setpoints, characterized by a rapid heating phase followed by stable steady-state operation. This response pattern reflects the effective integration of the electrical heating unit with the embedded temperature control strategy.

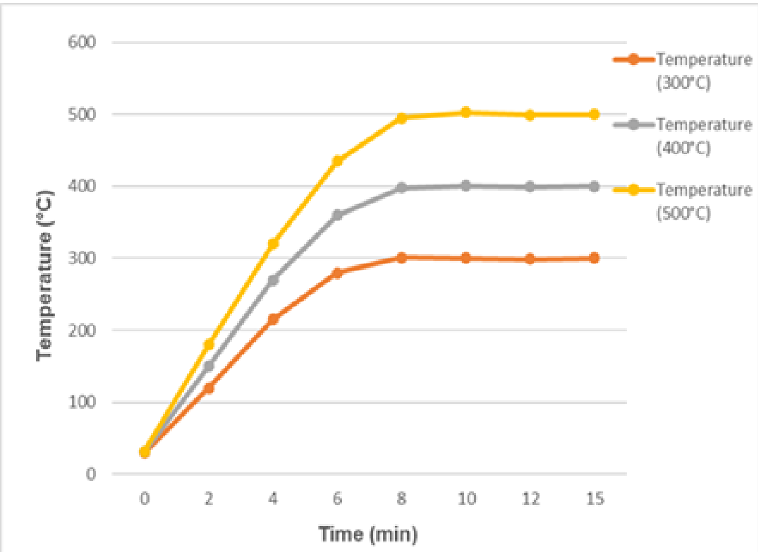

Fig. 4. Temperature response of the control system at different setpoints (300°C, 400°C, and 500°C)

During the initial heating phase, all curves exhibit a steep temperature rise, indicating that the heating power supplied by the electrical heater is sufficient to overcome the thermal inertia of the reactor system. The relatively short time required to reach each setpoint, even at 500°C, highlights the advantage of using an electrically driven heating mechanism in laboratory-scale thermal systems [17],[18]. As the operating temperature increases, a slight extension of the heating duration is observed, which can be attributed to increased heat losses and higher thermal mass at elevated temperatures [19],[20]. Once the desired temperature is reached, the system transitions into steady-state operation with minimal temperature fluctuation. The absence of significant overshoot at all setpoints suggests that the hysteresis-based on–off control strategy effectively limits excessive heating and prevents unstable temperature behavior. At higher setpoints, particularly at 500°C, minor temperature variations become more apparent; however, these fluctuations remain within an acceptable range and are consistent with the expected thermal dynamics of high-temperature systems. The comparative behavior across different setpoints demonstrates that the control system maintains consistent performance despite varying thermal demands. This indicates that the implemented control strategy is robust and adaptable, making it suitable for laboratory-scale thermal processing applications that require reliable and repeatable temperature regulation. Overall, the observed results confirm that the proposed embedded temperature control system provides a practical and effective solution for achieving stable thermal conditions in high-temperature experimental environments.

3.2. Stability Analysis of the Temperature Control System

The stability of the embedded temperature control system was evaluated to assess its capability to maintain the operating temperature consistently around the desired setpoint after steady-state conditions were achieved. The analysis is based on the experimental temperature data summarized in Table 3 and focuses on steady-state temperature deviation, fluctuation range, and the influence of operating temperature on control performance.

Tabel 3. Contoh penyimpangan suhu dan rentang stabilitas pada berbagai setpoint

Setpoint (°C)	Steady-state Time Interval (min)	Minimum Temperature (°C)	Maximum Temperature (°C)	Average Temperature (°C)	Deviation (±°C)
300	8–15	299	301	300.0	±1.0
400	8–15	398	401	399.7	±1.5
500	10–15	499	503	500.5	±2.5

As shown in Table 3, the system exhibits stable temperature regulation at all tested setpoints once steady-state conditions are reached. At the 300°C setpoint, the temperature is maintained within a narrow range of 299–301°C, resulting in a maximum deviation of ±1.0°C. This low deviation indicates that the control system performs effectively at moderate operating temperatures, where thermal inertia and heat losses remain relatively limited. At the 400°C setpoint, the steady-state temperature fluctuates between 398°C and 401°C, corresponding to a deviation of ±1.5°C. Compared to the 300°C operation, the slightly higher deviation reflects increased thermal losses and a higher control effort required to maintain thermal equilibrium. Nevertheless, the system maintains a consistent temperature without observable drift during prolonged operation, indicating stable control behavior. When operating at the highest setpoint of 500°C, the system shows a further increase in temperature fluctuation, with steady-state values ranging from 499°C to 503°C and a deviation of ±2.5°C. Compared to lower setpoints, this increase is attributed to greater thermal inertia and residual heat stored in the heating element and reactor structure at elevated temperatures [21],[22] A brief temperature overshoot is observed during the transition to steady-state; however, the system is able to compensate for this effect and reestablish stable temperature regulation within a short period.

The observed trend—where temperature deviation increases with higher operating setpoints—is consistent with fundamental thermal system behavior. At elevated temperatures, convective and radiative heat losses become more pronounced, and the dynamic response of the system becomes slower. Despite these challenges, the implemented hysteresis-based on–off control strategy effectively limits excessive temperature oscillations and prevents frequent actuator switching, thereby contributing to stable long-term operation [23],[24],[25], [26]. Overall, the results demonstrate that the proposed embedded temperature control system provides stable and repeatable temperature regulation across a range of operating conditions relevant to laboratory-scale thermal processing. While the achieved stability is not intended for applications requiring high-precision temperature control, it is adequate for experimental pyrolysis studies and similar laboratory-scale processes where controlled thermal conditions and repeatability are the primary requirements.

3.3. Control Response and System Reliability

The thermal control performance of the proposed system was evaluated at three temperature setpoints, namely 300 °C, 400 °C, and 500 °C, to assess the system's dynamic response, steady-state stability, and control reliability under varying thermal loads. The corresponding temperature responses and heater switching behaviors are presented in Fig. 5, Fig. 6, and Fig. 7.

At the 300 °C setpoint (Fig. 5), the temperature increases rapidly during the initial heating phase and reaches the target value within approximately 8 minutes. During this phase, the heater remains continuously active, indicating that sufficient heating power is supplied to overcome the thermal inertia of the system. Once the temperature approaches the setpoint, the heater is switched off and subsequently operates intermittently to maintain stable conditions. This behavior indicates effective control action, with temperature fluctuations remaining minimal and no significant overshoot observed.

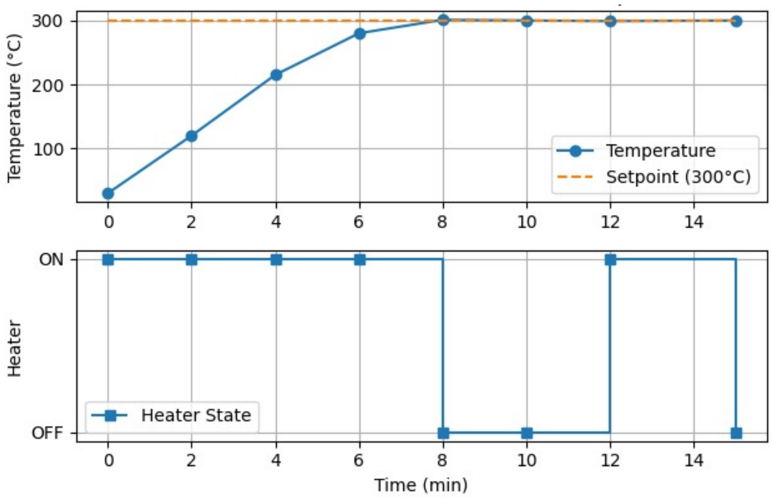

Fig. 5. Temperature response of the heating system toward the 300 °C setpoint during the heating process

At the 400 °C setpoint (Fig. 6), a similar response pattern is observed, although the heating rate slightly decreases due to the increased thermal demand. The system reaches the target temperature within approximately 8–10 minutes and transitions into steady-state operation. Heater switching occurs selectively near the setpoint, reflecting the role of the hysteresis-based on–off control strategy in balancing heat input and thermal losses. The limited temperature oscillation observed in this condition confirms stable control performance at higher operating temperatures.

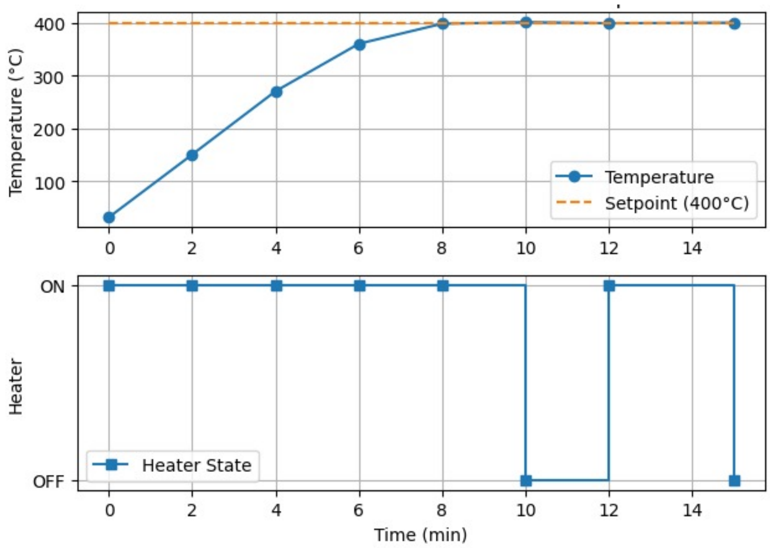

Fig. 6. Temperature response of the heating system toward the 400 °C setpoint during the heating process

At the highest setpoint of 500 °C (Fig. 7), the system demonstrates a consistent heating response despite the significantly increased thermal load. The temperature approaches the setpoint within a comparable time frame, followed by a small transient overshoot before the heater is deactivated. This response reflects the influence of residual heat stored in the heating element and reactor structure. After the transient phase, the control system restores stable operation through intermittent heater activation, indicating that the implemented control strategy remains effective under high-temperature conditions.

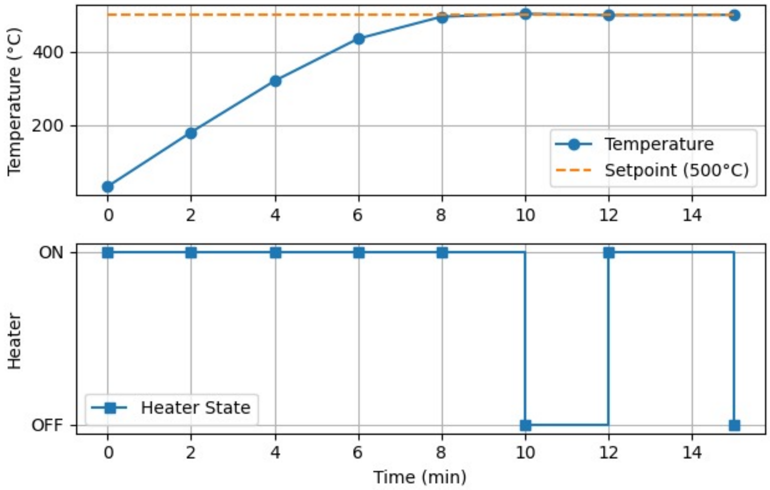

Fig. 7. Temperature response of the heating system toward the 500 °C setpoint during the heating process

Across all tested setpoints, the heater switching behavior follows a consistent pattern: continuous activation during the heating phase and intermittent operation only within the steady-state region. This pattern confirms that the control system avoids unnecessary actuator switching during temperature ramp-up and applies corrective action only when required [27],[28]. Such behavior reduces actuator stress and contributes to the overall reliability of the system [29],[30]. Overall, the experimental results demonstrate that the proposed thermal control system provides stable and repeatable temperature regulation across a wide operating range. Despite increased thermal inertia and heat losses at higher temperatures, the control system maintains acceptable stability without exhibiting abnormal behavior or control instability. These findings confirm that the implemented hysteresis-based on–off control strategy is suitable for laboratory-scale thermal processing applications, including pyrolysis processes that require controlled and reliable high-temperature operation.

3.4. Application Case Study: Pyrolysis Operation

The integrated temperature control system was applied to a laboratory-scale pyrolysis process as an application case study to evaluate its operational reliability under prolonged thermal exposure. In this study, the holding time at each temperature setpoint was set to 1 hour to ensure sufficient thermal decomposition while maintaining stable temperature conditions throughout the process. The results presented in this section aim to demonstrate the effect of stable temperature regulation on the consistency of the pyrolysis process rather than to optimize product yield.

Tabel 4. Representative mass reduction during pyrolysis operation (holding time: 1 hour)

Setpoint (°C)	Initial Mass (g)	Final Mass (g)	Mass Reduction (%)
300	100	68	32
400	100	52	48
500	100	39	61

The results indicate an increasing mass reduction with higher operating temperatures, which is consistent with the thermal decomposition behavior of polymer-based medical waste materials during pyrolysis. At 300 °C, the observed mass reduction is primarily associated with the release of moisture and the decomposition of low-molecular-weight volatile compounds. As the temperature increases to 400 °C, enhanced devolatilization and thermal cracking contribute to a more pronounced reduction in solid residue [31],[32].

At the highest operating temperature of 500 °C, the mass reduction reaches its maximum value, reflecting the dominance of secondary cracking reactions and further degradation of polymer chains. The extended holding time of 1 hour allows the pyrolysis reactions to proceed more completely, resulting in a lower residual mass while maintaining stable thermal conditions [33],[34].

These representative results demonstrate that stable temperature control enables consistent thermal processing during extended operation periods. The absence of abnormal temperature fluctuations during the holding phase confirms the reliability of the proposed control system under sustained high-temperature conditions. However, it should be emphasized that the presented data are not intended to characterize pyrolysis efficiency or product distribution. Instead, they serve to validate the functional applicability of the proposed temperature control system for laboratory-scale pyrolysis processes involving medical waste materials.

4. Conclusion

This study has presented the design and implementation of an embedded temperature control system for laboratory-scale thermal processing, with pyrolysis used as an application case study. The proposed closed-loop system integrates temperature sensing, microcontroller-based control, and electrical heating actuation to achieve stable and reliable temperature regulation under high-temperature operating conditions. Experimental results show that the hysteresis-based on–off control strategy is able to maintain consistent temperature control at setpoints of 300 °C, 400 °C, and 500 °C. The system demonstrates rapid heating response, minimal overshoot, and stable steady-state behavior, with temperature deviations remaining within acceptable limits despite increased thermal inertia at higher operating temperatures. Long-duration operation further confirms that the system operates reliably without excessive temperature oscillations or frequent actuator switching.

The main contribution of this work lies in the practical realization and performance evaluation of an embedded temperature control system specifically tailored for laboratory-scale thermal equipment. The findings indicate that a properly implemented on–off control approach provides a robust and cost-effective solution for experimental thermal processing applications. Future work may focus on the integration of advanced control methods and monitoring features to further enhance system performance and functionality.

Author Contributions

Ahmad Robittah: Conceptualization, project administration, and writing – original draft. **Ahmad Faqih Habibi**: Investigation and data curation. **Hafiz Al Farizi**: Software and visualization. **Achmadi**: Methodology, resources, and supervision. **Aulia Rahman**: Formal analysis, validation, and writing – review and editing. No funding support was received.

Funding

This research was funded by Politeknik Unggulan Kalimantan through the Internal Research Grant Program. The funding institution had no role in the study design, data collection, data analysis and interpretation, manuscript preparation, or the decision to submit the article for publication.

Declaration of Conflicting Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Acknowledgment

The authors gratefully acknowledge Politeknik Unggulan Kalimantan for providing financial support, laboratory facilities, and institutional assistance during the completion of this research.

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