ISSN: 2688-8645

A High-Precision Constant Temperature Control System for Microenvironments in Industrial HVAC Systems

Xiyuan Zhang [1], Menghan Pan [1], Lingxin Hu [1] and Tengteng Ma [2,*]

[1] School of Art and Design, Xinyang College, Xinyang, Henan, 464000, China

[2] Intelligent Technology Center, CHN ENERGY Shendong Coal Group Co., Ltd, Yulin Shaanxi, 719315, China

* Corresponding Author: Tengteng Ma

Abstract

In industrial HVAC (Heating, Ventilation, and Air Conditioning) systems, precise temperature control is critical for ensuring process stability, product quality, and equipment reliability. To address the demand for high-precision temperature regulation in localized microenvironments within industrial settings, a high-precision constant temperature control system was developed for industrial HVAC applications. This system utilizes an Arduino Uno microcontroller, integrated with DS18B20 digital temperature sensors and NTC thermistors, and employs a PID algorithm combined with relay feedback tuning to achieve adaptive, high-precision temperature control. Extensive operational testing demonstrates that the system can rapidly respond to and accurately regulate microenvironment temperatures in complex and variable industrial conditions, achieving temperature control accuracies of ±0.2°C for cooling and ±0.4°C for heating. This solution provides an efficient and stable temperature management approach for industrial HVAC systems.

Keywords

Industrial HVAC; Temperature Control; PID Algorithm; Semiconductor Cooling.

1. Introduction

Temperature is a critical physical parameter in industrial HVAC (Heating, Ventilation, and Air Conditioning) systems, directly affecting production efficiency, equipment operational stability, and product quality. The evolution of temperature control technology can be traced back to ancient civilizations, such as the use of solar energy or underground chambers for rudimentary temperature regulation in ancient Egypt. During the Industrial Revolution, the advent of mechanized production led to the development of temperature control systems based on mechanical devices and thermal sensors, such as thermometers and thermocouples. These systems were applied to heating, cooling, and constant temperature control in industrial processes but suffered from low precision and susceptibility to external environmental interference. In the early 20th century, advancements in electronics gave rise to electronic temperature control systems, which utilized components like resistors and thermistors for temperature measurement and actuators such as heating wires and solenoid valves for regulation. These systems significantly improved control accuracy and stability, becoming widely adopted in industrial applications. However, the precision of traditional systems remained limited, failing to meet the stringent requirements of modern industrial temperature control[1].

To address these needs, this study proposes a high-precision constant temperature control system for microenvironments in industrial HVAC systems, based on a microcontroller. The system integrates semiconductor cooling modules and ceramic heating elements, employing a

ISSN: 2688-8645

PID control algorithm and embedded technology to achieve high-precision temperature monitoring and regulation. Designed to meet the stringent temperature control requirements of applications such as semiconductor manufacturing and data center cooling, this system aims to advance the development and adoption of temperature control technologies in industrial HVAC systems.

2. Literature Review

Temperature control systems are critical in industrial HVAC (Heating, Ventilation, and Air Conditioning) applications, where precise and stable temperature regulation is essential for production efficiency, equipment reliability, and product quality[2]. With increasing demand for high-precision temperature control in specialized industrial settings such as semiconductor manufacturing, data center cooling, and precision machining, recent research has focused on enhancing the performance, intelligence, and adaptability of microenvironment temperature control systems.

Microcontroller-based intelligent temperature control systems have made significant strides. Leveraging embedded technology, these systems enable real-time data acquisition, processing, and control, offering compact, cost-effective, and easily deployable solutions for industrial applications. Integration with advanced monitoring interfaces further enhances system intelligence, enabling precise temperature regulation in distributed HVAC environments[3].

Advancements in control algorithms have addressed challenges such as nonlinearity, time delays, and environmental disturbances. Enhanced PID control strategies, including fuzzy PID and adaptive PID, have been widely studied to improve control accuracy and response speed[4]. Fuzzy logic-based approaches support dynamic parameter adjustment, making them suitable for HVAC systems with variable thermal loads. Adaptive PID methods, often incorporating multi-sensor inputs, allow real-time parameter tuning, enhancing stability and precision in dynamic industrial settings.

Current research trends emphasize integrating intelligent microcontroller systems with advanced control algorithms, such as fuzzy PID, adaptive PID, and neural network PID, to achieve high-precision temperature regulation. These advancements provide a robust foundation for developing compact, efficient, and adaptable temperature control systems, addressing the stringent requirements for microenvironment temperature control in industrial HVAC applications[5].

3. Control System Design

In industrial HVAC (Heating, Ventilation, and Air Conditioning) systems, high-precision constant temperature control in microenvironments is critical for ensuring production efficiency, equipment stability, and product quality, particularly in demanding applications such as semiconductor manufacturing, precision machining, and data center cooling, where temperature fluctuations can directly impact process accuracy and equipment longevity. To meet the requirements for high precision, rapid response, and reliability in these scenarios, this system employs an Arduino Uno microcontroller as the core, adopting a modular design approach. It integrates a temperature detection module, control module, cooling/heating module, and software control module to create an efficient and flexible high-precision constant temperature control system for microenvironments.

The system design accounts for the practical needs of industrial HVAC systems, selecting the Arduino Uno for its stable performance, rich development resources, and user-friendly programming interface, ensuring development efficiency and operational reliability. The temperature detection module uses high-precision sensors to collect real-time environmental temperature data, providing accurate inputs for the control algorithm. The control module, based on a PID algorithm with relay feedback tuning, dynamically adjusts the operation of cooling and heating actuators to achieve rapid response and high-precision temperature control. The cooling/heating module employs semiconductor cooling modules and ceramic heating elements, combined with a compact design and efficient heat dissipation, to meet the stringent requirements of microenvironment temperature control. The software control module, implemented through modular programming, handles system initialization, data processing, and user interaction, ensuring operational efficiency and maintainability. The system design diagram is shown in Figure 1.

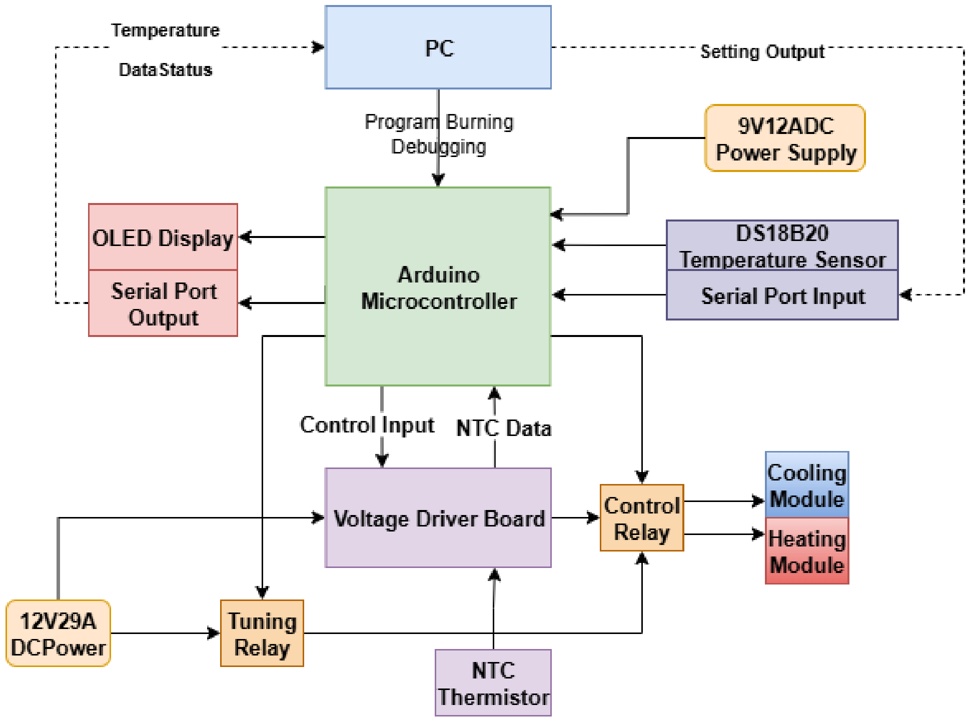

Figure 1. System Design Diagram

3.1. Control System Hardware Design

The system is built around an Arduino Uno microcontroller, utilizing a modular hardware design that includes a temperature detection module, control module, cooling/heating module, display and input module, and serial communication module to provide high-precision constant temperature control for microenvironments in industrial HVAC systems. The temperature detection module combines DS18B20 digital temperature sensors and NTC thermistors for high accuracy and robust interference resistance[6]. The cooling/heating module consists of 12706 semiconductor cooling modules and ceramic heating elements. A display and keypad module enables human-machine interaction, supporting target temperature settings and status monitoring. The serial communication module uploads real-time temperature data to a host computer, facilitating remote monitoring and data analysis in industrial environments. The overall design is compact and reliable, providing a solid foundation for high-precision temperature control in industrial HVAC systems[7].

3.1.1. System Controller Selection

In industrial HVAC systems, microenvironment temperature control tasks primarily involve PID control algorithms and real-time data processing, with moderate computational complexity and hardware requirements. Considering computational capability, control functionality, and development convenience, the Arduino Uno microcontroller was selected as the core controller. Its stable performance, extensive development resources, and straightforward programming

ISSN: 2688-8645

interface enable rapid implementation of control logic, reducing development time. The Arduino Uno's compatibility and scalability also support future upgrades, such as integration with industrial IoT interfaces or remote monitoring modules, providing an efficient and cost-effective control solution for industrial HVAC systems.

3.1.2. Temperature Control Solution Selection

To meet the high-precision constant temperature control needs of microenvironments in industrial HVAC systems, the system employs semiconductor cooling technology and ceramic heating elements. Semiconductor cooling offers low thermal inertia, high response speed, and precise temperature control, making it ideal for space-constrained industrial applications such as semiconductor manufacturing equipment or data center cooling systems. Compared to traditional vapor-compression refrigeration, the 12706 semiconductor cooling module is compact, easily integrated into miniaturized designs, and capable of rapid response to temperature changes while maintaining stable conditions.

For heating, ceramic heating elements were chosen for their uniform heat distribution and high stability. The excellent thermal conductivity of ceramic materials ensures even temperature distribution within the microenvironment, with no noise or vibration, meeting the stringent requirements for stability and quiet operation in industrial HVAC systems.

3.1.3. Temperature Detection Module Design

The temperature detection module integrates DS18B20 digital temperature sensors and NTC thermistors to achieve high-precision and rapid-response temperature measurement. NTC thermistors, made from materials such as iron oxide and zinc oxide, offer fast response and high sensitivity, accurately reflecting environmental temperature changes through resistance variations, making them suitable for dynamic temperature monitoring in industrial HVAC systems. The DS18B20 digital temperature sensor connects to the Arduino Uno via a single-bus protocol, collecting temperature data once per second with an accuracy of ±0.5°C[8]. Its digital output eliminates the need for an external analog-to-digital converter, simplifying the hardware design. The complementary use of both sensors ensures stable and reliable temperature measurements in complex industrial environments.

3.1.4. Control Module Design

The control module, centered on the Arduino Uno, processes temperature sensor data, executes the PID control algorithm, and adjusts the operation of the cooling and heating modules. The PID algorithm dynamically regulates cooling and heating power based on the deviation between the set and actual temperatures, achieving rapid response and high-precision control. Since the Arduino Uno's digital output ports (5V, low current) cannot directly drive high-power devices, relays are used as power control intermediaries. These relays convert low-power signals from the microcontroller into switching signals for high-power loads, driving the 12706 cooling modules and ceramic heating elements.

The relay circuit incorporates freewheeling diodes and overcurrent protection to prevent reverse current damage to the microcontroller and handle sudden overloads, ensuring safety and stability in industrial environments. The control module implements relay on/off control through programming, forming a complete cooling/heating circuit to ensure efficient system operation.

3.1.5. Cooling/Heating Module Design

Based on thermal load calculations for the temperature control chamber in the industrial HVAC system, the chamber has internal dimensions of 233 mm × 136 mm × 165 mm, with a 15 mm thick polyurethane foam insulation layer, resulting in a heat leakage of 13.7336 W. Accounting for door-opening heat loss, stored item heat, and other losses, the total thermal load is 29.0225 W, with a 10% margin yielding a design thermal load of 33.3793 W[9].

The cooling module employs two 12706 semiconductor cooling modules, each with a cooling capacity of 31.8 W, meeting the high thermal load requirements of the microenvironment. A water-cooling system, equipped with three air-cooled radiator modules and a water pump, ensures efficient heat dissipation and stable operation of the cooling modules. The heating module uses two ceramic heating elements (12V, 2A, rated power 20 W, maximum temperature 80°C) [10], capable of rapidly achieving target temperature increases to meet the fast heating demands of industrial HVAC systems.

3.2. Control System Software Design

The system software adopts a modular design with clear logic and strong scalability, optimized for high-precision constant temperature control in microenvironments within industrial HVAC systems. The main program handles system initialization and collects temperature data via timed interrupts, ensuring real-time accuracy. The core control logic, based on the PID algorithm, dynamically adjusts the operation of the cooling and heating modules. The user interaction module responds to keypad inputs, supporting target temperature settings and real-time status display. To accommodate varying scales of temperature-controlled environments in industrial HVAC systems, the system employs relay feedback tuning for automatic PID parameter adjustment. The data communication module uploads temperature data to a host computer via serial communication, facilitating remote monitoring and data analysis in industrial settings. These modules work synergistically to ensure high control accuracy and operational stability in complex industrial environments.

3.2.1. Control Algorithm Implementation

The core control algorithm is based on PID control, which calculates the error between the target and current temperatures in real time to dynamically adjust the operation of the 12706 semiconductor cooling modules and ceramic heating elements. The PID algorithm is simple to implement, with a straightforward structure and easily adjustable parameters, making it suitable for various control objects. It offers excellent real-time performance, rapid response to environmental changes, and high reliability, with robust stability and tolerance to parameter variations and disturbances[11].

The PID algorithm relies on three parameters: proportional gain, integral time, and derivative time. Proportional control enhances response speed by immediately addressing errors but may introduce steady-state errors. Integral control eliminates steady-state errors, improving accuracy. Derivative control predicts error trends, making proactive adjustments to enhance system stability.

In computer-based control, as a sampling-based method, the control output is calculated based on discrete error values. Thus, the PID formula is discretized into positional or incremental forms. Positional PID control directly computes the control output at the current position, while incremental PID control calculates the change in control output relative to the previous moment[12].

3.2.2. Tuning Algorithm Implementation (Relay Feedback Tuning)

To optimize PID parameters, the system employs relay feedback tuning, which generates an oscillatory waveform by varying the controller’s output to determine PID parameters. First, the maximum and minimum PID output values are set (e.g., 100% and 0% duty cycle for a temperature control system) [13]. A typical target value, such as 50°C within a 0–80°C range, is selected. When the measured temperature is below the setpoint, the maximum output is applied; when above, the minimum output is used. After at least three oscillation cycles, the system extracts characteristic parameters, such as oscillation period and amplitude, to calculate PID parameters[14].

Relay feedback tuning operates in two modes: testing and regulation. In testing mode, the controller switches to bang-bang control, outputting full scale when the measured value is below the setpoint and zero when above, inducing oscillations. After at least three cycles, the oscillation waveform yields the oscillation period (Tu) and amplitude (A), from which the critical gain (Kc) and critical period (Tc) are derived[15]. Using the Ziegler-Nichols method, PID parameters are determined based on the following empirical table 1:

Table 1. Ziegler-Nichols Tuning Parameters for PID Controllers

Controller Type	Proportional Gain (Kp)	Integral (Ti)	Derivative (Td)
P Control	0.5 Kc	\	\
PI Control	0.45 Kc	Tc/1.2	\
PID Control	0.6 Kc	Tc/2	Tc/8

Relay feedback tuning is simple and widely applicable, requiring minimal equipment or data, making it ideal for resource-constrained controllers. By generating oscillatory waveforms, it intuitively reveals system dynamics, enabling rapid parameter extraction. However, it is susceptible to noise, which may lead to measurement errors, and soft serial communication consumes additional resources, potentially affecting real-time performance and accuracy.

In this high-precision constant temperature control system, relay feedback tuning was chosen for its simplicity and effectiveness in resource-limited environments. It adapts to dynamic system changes, ensuring robust control performance across various operating conditions. While noise and real-time issues exist, careful parameter tuning and post-implementation debugging mitigate these challenges, ensuring excellent performance in practical applications.

3.2.3. Host Computer Data Reception and Storage Software Design

The host computer software, developed using Qt5, supports data reception, storage, and analysis for industrial HVAC systems. The user interface comprises five functional modules: serial connection, serial data reading, baud rate adjustment, data storage, and data analysis. The serial connection module establishes communication with external devices, the serial reading module retrieves data, the baud rate adjustment module allows parameter configuration, the data storage module saves received data locally, and the data analysis module processes and analyzes data, displaying results in the lower-left corner of the UI.

This software enhances remote monitoring and data management in industrial settings, improving system operability and data traceability[16].

4. Results

4.1. Constant Temperature Testing

As shown in Figure 2, the heating test was conducted with an initial ambient temperature of 25°C and a target temperature of 46°C, simulating the heating requirements of precision equipment in industrial HVAC systems. The results demonstrate that the system reached the target temperature within approximately 1 minute and maintained stability. Although minor temperature overshoot occurred before stabilization, the steady-state temperature fluctuation was kept within ±0.4°C. Even in the worst-case scenario, fluctuations did not exceed ±0.7°C, with peak fluctuations remaining below ±1°C.

As shown in Figure 3, the cooling test was performed with an initial ambient temperature of 25°C and a target temperature of 2°C, simulating low-temperature scenarios such as data center cooling. The system achieved the target temperature within approximately 3 minutes and maintained stability, with temperature fluctuations controlled within ±0.2°C and peak fluctuations not exceeding ±0.4°C.

ISSN: 2688-8645

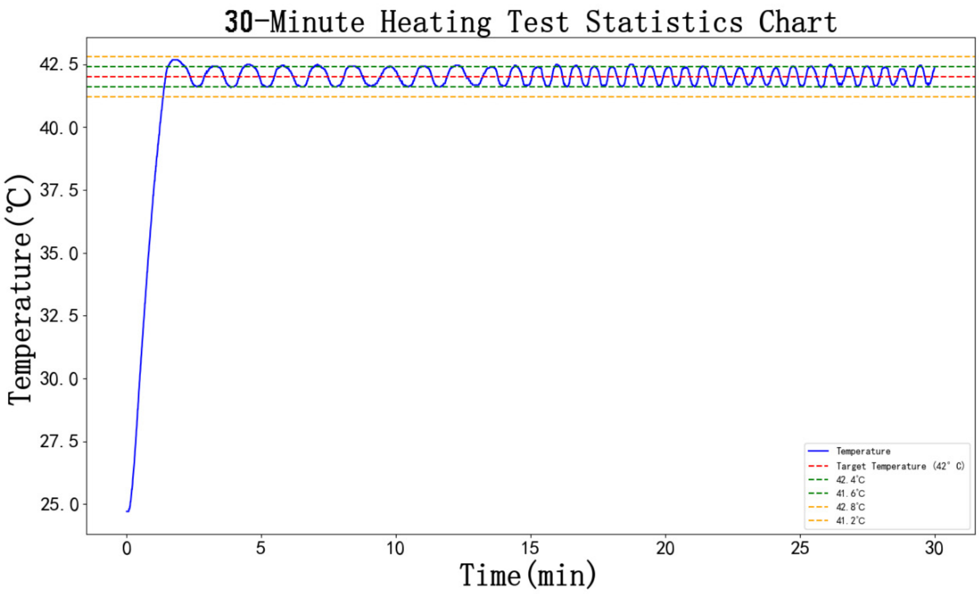

Figure 2. Heating Test Results

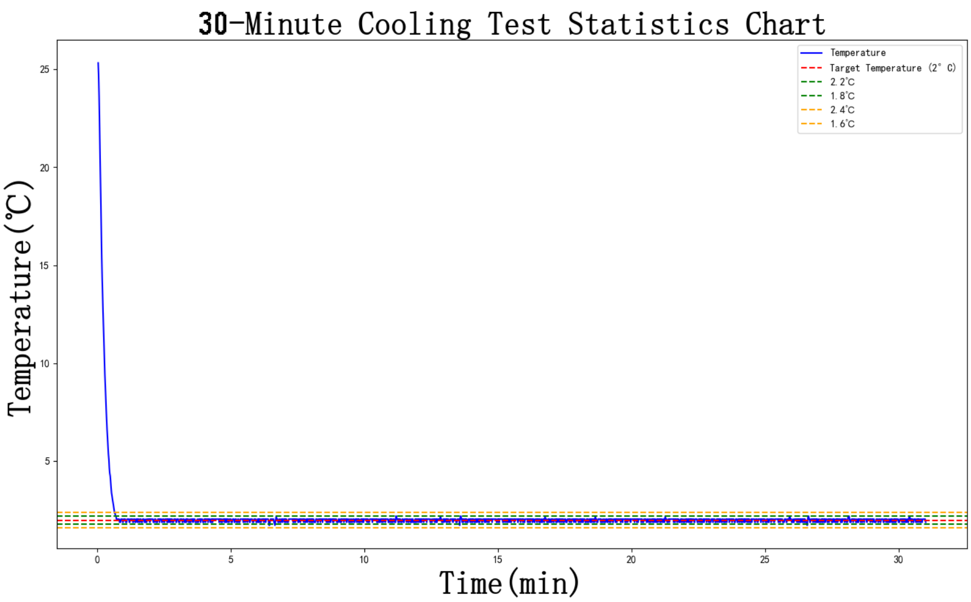

Figure 3. Cooling Test Results

Table 2. Constant Temperature Test Data

Test Type	Target Temperature (°C)	Mean (°C) (after 5 min)	Min (°C) (after 5 min)	Max (°C) (after 5 min)	Standard Deviation
8-Hour Cooling	2.0	2.01	1.74	2.23	0.573
8-Hour Heating	42.0	41.93	41.58	42.55	0.137
30-Minute Cooling	2.0	2.03	1.74	2.22	0.680
30-Minute Heating	42.0	42.09	41.55	42.47	0.079

Analysis of the test data in Table 2 demonstrates the system’s robust performance across various operating conditions. An 8-hour cooling test yielded an average temperature of 2.01°C with a standard deviation of 0.57281, indicating high stability during prolonged low-

ISSN: 2688-8645

temperature operation. An 8-hour heating test resulted in an average temperature of 41.92534°C with a standard deviation of 0.13692, confirming excellent temperature control in high-temperature environments. A 30-minute heating test showed an average temperature of 42.08878°C with a standard deviation of 0.07887, reflecting high-precision response in short-term operation. Similarly, a 30-minute cooling test recorded an average temperature of 2.03°C with a standard deviation of 0.68007, demonstrating rapid stabilization.

4.2. Self-Tuning Testing

To verify the system's adaptability across diverse industrial HVAC scenarios, self-tuning tests were conducted using temperature control chambers of varying sizes, with an ambient temperature of 37°C and a target temperature of 5°C, simulating the temperature control needs of precision machining or semiconductor manufacturing. As shown in Table 3, initial tests using default PID parameters (P=100, I=50, D=20) resulted in temperatures approaching the target but with significant errors. After optimization using relay feedback tuning, new parameters (P=56, I=21, D=5) were obtained. Subsequent tests demonstrated that the system maintained temperature errors within ±0.2°C after stabilization. Even under external disturbances, the system quickly recovered stability, consistently maintaining the target temperature.

Table 3. Self-Tuning Test Data

Test Phase	PID Parameters (P, I, D)	Temperature Deviation (°C)	Stabilization Time (min)
Initial Test	(100, 50, 20)	±4.8	Oscillation
Optimized Test	(56, 21, 5)	±0.2	~3
Disturbance Recovery Test	(56, 21, 5)	±0.2	~1

5. Discussion

The constant temperature test results demonstrate the system's excellent performance in both heating (target temperature: 46°C) and cooling (target temperature: 2°C) scenarios. The 8-hour heating test yielded an average temperature of 41.81534°C with a standard deviation of 0.13692, indicating exceptional stability during prolonged high-temperature operation, with temperature fluctuations maintained within ±0.4°C and peak fluctuations not exceeding ±1°C. Similarly, the 8-hour cooling test recorded an average temperature of 2.01°C with a standard deviation of 0.57281, maintaining fluctuations within ±0.2°C and peak fluctuations below ±0.4°C. These results confirm the system's ability to meet the high-precision temperature control requirements of industrial HVAC systems, particularly in low-temperature applications such as data center cooling and high-temperature scenarios like precision equipment heating.

Short-term tests further validated the system's rapid response capabilities. The 30-minute heating test achieved an average temperature of 42.26878°C with a standard deviation of 0.07887, demonstrating the system's ability to reach the target temperature in approximately 1 minute and stabilize quickly, making it suitable for industrial applications requiring fast response times. The 30-minute cooling test recorded an average temperature of 2.03°C with a standard deviation of 0.68007, showing rapid temperature regulation within 3 minutes, meeting the dynamic temperature control needs of industrial HVAC systems. Minor temperature overshoot observed during heating (peak: +0.8°C) converged rapidly upon stabilization, underscoring the efficiency and robustness of the PID control algorithm in dynamic regulation.

The self-tuning tests confirmed the effectiveness of the relay feedback tuning method. Initial PID parameters (P=100, I=50, D=20) resulted in significant errors (±4.8°C) and oscillations across temperature control chambers of varying sizes. After optimization using relay feedback tuning, the adjusted parameters (P=56, I=21, D=5) reduced errors to within ±0.2°C, with a stabilization time of approximately 3 minutes. Disturbance recovery tests showed that the system restored the target temperature of 5°C within approximately 1 minute after external disturbances, demonstrating strong adaptability and interference resistance. This self-tuning capability significantly enhances the system's applicability in diverse industrial environments, such as temperature control chambers of different sizes or scenarios with dynamic thermal loads.

6. Conclusion

This study designed and implemented a high-precision constant temperature control system for microenvironments in industrial HVAC systems, based on the Arduino Uno microcontroller. The system integrates DS18B20 digital temperature sensors, NTC thermistors, 12706 semiconductor cooling modules, and ceramic heating elements, employing a PID control algorithm with relay feedback tuning to achieve high-precision temperature control targets of ±0.2°C in cooling mode and ±0.4°C in heating mode. Test results demonstrate the system's rapid response, high stability, and modular design, effectively meeting the stringent temperature control requirements of industrial HVAC applications, such as semiconductor manufacturing, data center cooling, and precision machining. This system provides an efficient and reliable solution for temperature control in industrial environments.

Acknowledgments

All authors made equal contributions to the study. Specifically, Authors Xiyuan Zhang and Tengteng Ma drafted the initial manuscript and performed subsequent revisions.

This work was supported by the Employee Innovation and Efficiency Program of the Intelligent Technology Center, Shendong Coal Group, CHN ENERGY, for the first half of 2025. The financial support provided the necessary resources for the design, implementation, and evaluation of the system presented in this study.

References

[1] Wang Bing. Design of a Semiconductor Cooling Box Based on Arduino Microcontroller [D]. Southwest Jiaotong University, 2020.

[2] Zhang Lulu. Design and Implementation of a Microcontroller-Based Temperature Measurement and Control System [D]. Jilin University, 2014.

[3] Peng Mengdi. Research and Implementation of a High-Precision Temperature Measurement and Control System [D]. Taiyuan University of Technology, 2021.

[4] Qiao Guan. Research on an Intelligent Coffee Roasting System Based on Adaptive Temperature Control [D]. Hangzhou Dianzi University, 2021.

[5] Qin Shixuan. Research on an Adaptive PID Temperature Control System [D]. Changchun University of Science and Technology, 2018.

[6] Kundu S, Sinitsyn N, Backhaus S, et al. Modeling and control of thermostatically controlled loads[J]. arXiv preprint arXiv:1101.2157, 2011.

[7] Singhala P, Shah D, Patel B. Temperature control using fuzzy logic[J]. arXiv preprint arXiv: 1402. 3654, 2014.

[8] Liang H, Sang Z K, Wu Y Z, et al. High precision temperature control performance of a PID neural network-controlled heater under complex outdoor conditions[J]. Applied Thermal Engineering, 2021, 195: 117234.

ISSN: 2688-8645

[9] Możaryn J, Petryszyn J, Ozana S. PLC based fractional-order PID temperature control in pipeline: design procedure and experimental evaluation[J]. Meccanica, 2021, 56: 855-871.

[10] Kawasaki Y, Yoneda Y. Local temperature control in greenhouse vegetable production[J]. The Horticulture Journal, 2019, 88(3): 305-314.

[11] Villegas-Uribe C A, Alcántara-Avila J R, Medina-Herrera N, et al. Temperature control of a Kaibel, Agrawal and Sargent dividing-wall distillation columns[J]. Chemical Engineering and Processing-Process Intensification, 2021, 159: 108248.

[12] Khalid M, Omatu S. A neural network controller for a temperature control system[J]. IEEE control systems magazine, 1992, 12(3): 58-64.

[13] Jeroish Z E, Bhuvaneshwari K S, Samsuri F, et al. Microheater: material, design, fabrication, temperature control, and applications—a role in COVID-19[J]. Biomedical microdevices, 2022, 24: 1-49.

[14] Ruelens F, Claessens B J, Vandael S, et al. Residential demand response of thermostatically controlled loads using batch reinforcement learning[J]. IEEE Transactions on Smart Grid, 2016, 8(5): 2149-2159.

[15] Nazir M S, Hiskens I A. Noise and parameter heterogeneity in aggregate models of thermostatically controlled loads[J]. IFAC-PapersOnLine, 2017, 50(1): 8888-8894.

[16] Brandi S, Piscitelli M S, Martellacci M, et al. Deep reinforcement learning to optimise indoor temperature control and heating energy consumption in buildings[J]. Energy and Buildings, 2020, 224: 110225.