Design and Experimental Study of an Arduino-Based Intelligent Building Hot Water Temperature Control System

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Abstract. Temperature fluctuations in domestic hot water systems are common in intelligent buildings, and they can affect both user comfort and energy efficiency. In this study, an Arduino-based water temperature control system was developed using a Proportional-Integral-Derivative (PID) controller. The system includes a temperature sensing module, a control module, and a valve actuation module, which work together to adjust the mixing ratio of hot and cold water and keep the outlet temperature close to the target value. A prototype platform was built to simulate the hot water mixing process in an intelligent building environment. Different PID parameter settings were tested and compared to examine their influence on system performance. The experimental results showed that the system was able to reduce temperature fluctuations and improve temperature stability. The comparison of different parameter settings also showed that suitable proportional and integral actions helped achieve a balance between response speed and control stability. Based on the results, low-cost embedded control technology can be applied to hot water temperature regulation. The proposed system may be useful for domestic hot water management and could be applied in dormitories, apartments, hotels, and other intelligent building environments.

Keywords: Intelligent Building; Domestic Hot Water System; Arduino; PID Controller; Temperature Regulation.

1. Introduction

With the development of smart cities and intelligent building technologies, intelligent control of domestic hot water systems has become an important topic for improving residential comfort and energy efficiency [1]. In centralized hot water supply systems used in large residential buildings, apartments, and student dormitories, water temperature often changes because of ambient temperature variations, differences in user demand, and fluctuations in water supply pressure. These temperature changes not only reduce user comfort but may also affect system performance and energy efficiency. Maintaining a stable hot water temperature has therefore become an important challenge in intelligent building systems.

In recent years, many researchers have studied different methods for hot water temperature control. Tahiri et al. proposed a temperature-feedback hierarchical control strategy for domestic hot water storage systems in residential buildings [2]. By adding extra temperature sensors and adjusting control parameters under different operating conditions, the method improved system efficiency while maintaining user comfort and hygiene requirements. Fan et al. developed a PID-based temperature control method for electric water heating systems, which reduced temperature fluctuations and improved control accuracy and stability [3]. Liu et al. proposed an outlet water temperature control strategy that combines PID control and feedforward control [4]. Feedforward compensation was introduced to reduce the influence of inlet water temperature disturbances, which helped improve response speed and temperature stability. Most existing studies mainly focus on temperature control strategies and parameter optimization. Research on applying these control methods in intelligent building hot water systems through the integration of temperature sensors, actuators, and embedded controllers is still relatively limited. For this reason, this study develops a smart building hot water temperature control system based on Arduino UNO, temperature sensors, and actuator devices. A PID control algorithm is used to adjust the mixing ratio of hot and cold water, and experiments are carried out to evaluate the temperature control performance of the system and its ability to maintain a stable water temperature.

To solve the problem of temperature fluctuations in intelligent building hot water supply systems, this study builds a temperature control system based on Arduino UNO and a PID control algorithm. The system uses DS18B20 temperature sensors to collect real-time water temperature data and employs Arduino UNO as the main controller. Temperature errors are calculated through the PID algorithm, which generates control signals for the actuators and adjusts the mixing ratio of hot and cold water to keep the outlet temperature close to the target value. An experimental platform with a target temperature of 39°C was established to test the proposed system. Key indicators, including response time, overshoot, and steady-state error, were measured and analysed. The results were used to assess the performance of the Arduino-based PID control system in hot water temperature regulation. This study provides useful information for the design of low-cost intelligent temperature control systems and offers experimental support for future research on intelligent building hot water management systems.

2. Design of the Water Temperature PID Control System

2.1. Overall System Analysis

To achieve stable temperature control in centralized hot water supply systems for intelligent buildings, this study designed an intelligent temperature regulation system based on a PID control algorithm. The system continuously monitors the temperatures of the hot water pipeline, cold water pipeline, and user outlet. According to the difference between the target temperature and the actual outlet temperature, the openings of the hot and cold water control valves are adjusted automatically to keep the outlet temperature stable.

The system uses a closed-loop feedback control structure with four main parts: a temperature sensing module, a control module, an actuator module, and a hot–cold water mixing module. Temperature sensors continuously collect temperature data and send it to the controller. The controller calculates the control output through a PID control algorithm and drives the control valves to adjust the flow ratio of hot and cold water, helping maintain a stable outlet temperature. Building hot water systems usually have thermal inertia, transmission delays, and changes in user water demand. For this reason, a zoned mixing control strategy was selected. When the temperature difference is large, the system enters a rapid heating or rapid cooling mode. As the outlet temperature gets closer to the target value, the control strategy changes to a dual-valve coordinated adjustment mode to improve response speed and control accuracy.

To test the performance of the control strategy, a scaled-down Arduino-based experimental platform was developed. Servo motors were used to simulate motorized control valves in actual building hot water systems. Experimental data were collected and analysed to examine the control performance of the system. The Overall Architecture of the Proposed Smart Building Hot Water Temperature Regulation System is shown in Figure 1.

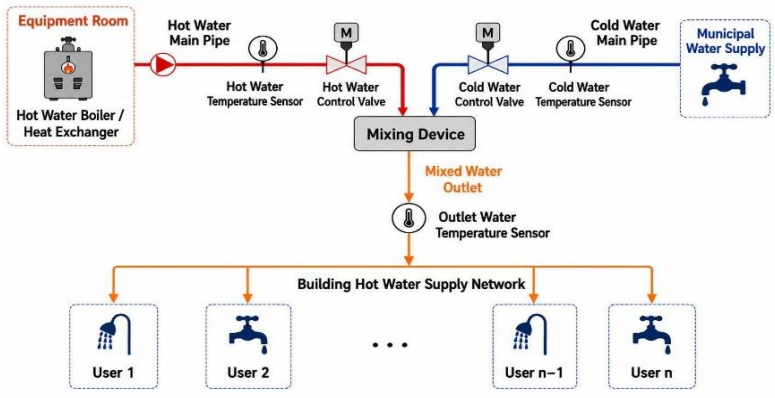


Fig 1. Overall Architecture of the Proposed Smart Building Hot Water Temperature Regulation System.

2.2. Hardware Design

2.2.1. Main Controller Unit

Arduino UNO was chosen as the main controller of the system and was used for temperature data collection, control algorithm processing, and actuator control. Arduino UNO is based on the ATmega328P microcontroller and provides sufficient processing capability, a mature development environment, and a large number of input/output interfaces, which makes it suitable for real-time control applications [5].

2.2.2. Temperature Sensing Module

The system uses DS18B20 digital temperature sensors for temperature measurement. The sensors are installed at the hot water inlet, cold water inlet, and mixed water outlet for real-time multi-point temperature monitoring. The DS18B20 sensor has high measurement accuracy, good noise resistance, and convenient digital communication, which makes it suitable for hot water temperature control applications [6].

2.2.3. Actuator Module

A servo motor is used as the actuator for valve control in the system. By changing the rotation angle of the servo motor, the openings of the hot and cold water valves can be adjusted, which changes the mixing ratio of hot and cold water. The servo motor is controlled through PWM signals generated by the Arduino and can achieve accurate positioning [7]. Compared with traditional on–off control methods, continuous valve adjustment provides better control accuracy and more stable system operation.

2.2.4. Hot–Cold Water Mixing Module

The hot–cold water mixing module is the main controlled part of the system. The system includes separate hot water and cold water inlets. Water from the two sources passes through independently controlled valves and then enters the mixing chamber, where the hot and cold water are mixed to produce water at the required temperature. Because of the large temperature difference between hot and cold water, as well as the thermal inertia and transport delay during the mixing process, the mixing module shows typical dynamic control behaviour [8].

2.2.5. Power Supply and Communication Module

During the experiment, a standard computer USB port was used to provide a 5 V power supply for the Arduino UNO. Operational data were transmitted through serial communication at a baud rate of 9600 bps. Serial communication was used because it is a simple and reliable way to transfer data in real time within embedded control systems [9].

2.3. PID Control Logic

The system uses a closed-loop feedback control structure, in which the user-defined temperature $\boldsymbol{T_{set}}$ is used as the target value. During system operation, temperature sensors continuously measure the outlet water temperature and send the data to the Arduino controller. The controller calculates the temperature error and produces control signals through a PID control algorithm. These signals adjust the openings of the hot and cold water valves, which changes the mixing ratio and keeps the outlet temperature close to the target value.

The temperature error is defined as:

$$e(t) = T_{set} - T_{current} \tag{1}$$

Where $\boldsymbol{T_{set}}$ represents the target temperature and $\boldsymbol{T_{current}}$ denotes the measured outlet temperature.

When the actual temperature is lower than the target temperature, the error is positive and the system increases the hot water flow rate. Conversely, when the actual temperature exceeds the target

temperature, the error becomes negative and the system increases the cold water flow rate. This mechanism forms a negative feedback control loop.

Considering the significant thermal inertia and transport delay of building hot water systems, a PID control algorithm is employed [10]. The control output is expressed as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad (2)$$

Where $\boldsymbol{K_p}$, $\boldsymbol{K_i}$, and $\boldsymbol{K_d}$ are the proportional, integral, and derivative gains, respectively.

The Block Diagram of the PID Control Algorithm is shown in Figure 2.

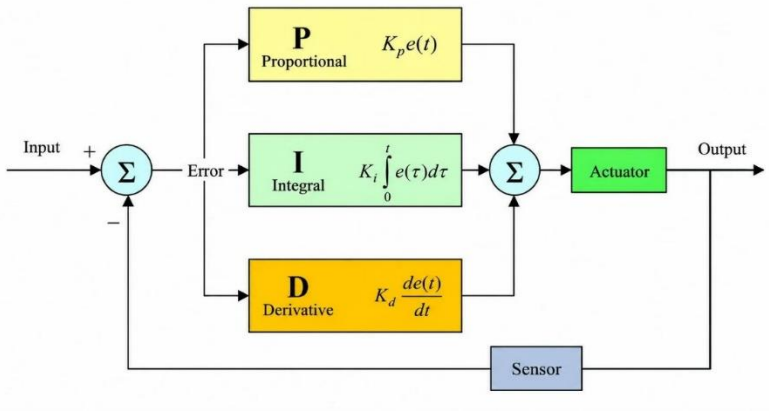


Fig 2. Block Diagram of the PID Control Algorithm.

The proportional term increases the response speed by producing a control action that is proportional to the temperature error. The integral term accumulates past errors to reduce steady-state error and improve long-term control accuracy. The derivative term responds to the rate of change of the error and helps reduce overshoot and oscillations.

A zoned mixing control strategy was also used to improve temperature control. When the outlet temperature differs greatly from the target value, the system enters a rapid adjustment stage, where only the hot water valve or the cold water valve is actively controlled. As the temperature gets closer to the target value, the controller switches to a dual-valve coordinated control mode. Both valves are adjusted at the same time to achieve more precise temperature regulation.

The specific control logic is defined as follows:

* When $\boldsymbol{T_{current} < T_{set} - 2}$℃, the system enters HEATING mode, and only the hot water valve is adjusted to rapidly increase the outlet temperature.

* When $\boldsymbol{T_{set} - 2}$℃$\leq \boldsymbol{T_{current}} \leq \boldsymbol{T_{set} + 2}$℃, the system enters DUAL_PID mode, where both hot and cold water valves are adjusted simultaneously to achieve precise temperature control.

* When $T_{current} > T_{set} + 2$℃, the system enters COOLING mode, and only the cold water valve is adjusted to rapidly reduce the outlet temperature.

3. Experimental Design and Analysis

3.1. Experimental Setup and Parameter Configuration

In practical large-scale building hot water systems, operating conditions are influenced by factors such as water supply pressure, pipeline length, and simultaneous water usage by multiple users, resulting in a highly complex operating environment. To emphasize the performance of the temperature control algorithm while reducing experimental complexity, the following simplifications were introduced in this study: (1) Laboratory hot and cold water sources were used to replace the actual building water supply system; (2) An SG90 servo motor was employed to drive the valves instead of industrial motorized control valves; (3) Short flexible tubes were used in place of long-distance water distribution pipelines; (4) Only temperature variations were considered in the control process, while fluctuations in water supply pressure were neglected.

To simulate the hot–cold water mixing process in practical building hot water systems, a dual-valve coordinated control strategy was adopted. Ball valves were installed in both hot and cold water pipelines, and servo motors were used to adjust valve openings. The servo rotation range was defined as 0°–90°, where 0° represents a fully open valve and 90° represents a fully closed valve. For the hot water valve, a fully open state diverts hot water away from the mixing chamber, resulting in a lower outlet temperature. Conversely, a fully closed state allows hot water to enter the mixing chamber, increasing the outlet temperature. The Valve Control Logic is shown in Table 1.

Table 1. Valve Control Logic.

Valve Type	0° (Fully Open)	90° (Fully Closed)
Hot Water Valve	Hot water bypassed (mixing path closed)	Hot water enters mixing chamber
Cold Water Valve	Cold water bypassed (mixing path closed)	Cold water enters mixing chamber

The Experiment Prototype of the Temperature Regulation System is shown in Figure 3.

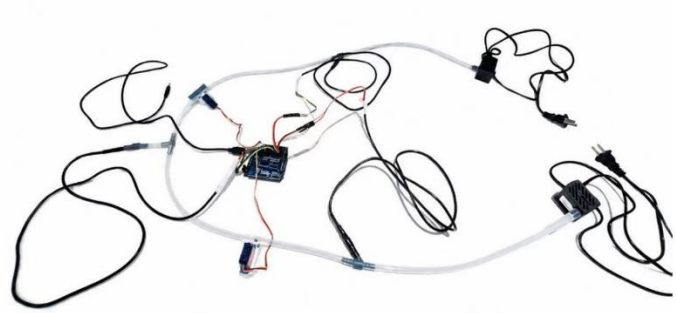


Fig 3. Experiment Prototype of the Temperature Regulation System.

3.2. Comparison of PID Parameter Configurations

To investigate the influence of PID parameters on system performance, the proportional (P), integral (I), and derivative (D) gains were adjusted. Four parameter configurations were designed and evaluated by comparing their effects on response speed, overshoot, and steady-state error. The PID Parameter Configurations is shown in Table 2.

Table 2. PID Parameter Configurations

Version	K_p	K_i	K_d	Integral Limit	Output Limit	Valve Step Size
v1	3.0	0.05	3.0	±50	errMax×5	5°
v2	1.2	0.02	0.0	±5	errMax×3	3°
v3	1.8	0.015	0.0	±5	errMax×3	3°
v4	1.5	0.05	0.0	±5	errMax×3	3°

As shown in the table, v1 used relatively large proportional and derivative gains to test the effect of high-gain control on system response speed. In v2, the proportional gain was reduced and the derivative term was removed to observe the control performance under low-gain conditions. Based on v2, the proportional gain in v3 was increased to study how stronger proportional action affected system responsiveness. In v4, a moderate proportional gain and a relatively large integral gain were selected to balance response speed, overshoot, and steady-state error, which resulted in better overall control performance.

3.3. Experimental Results and Analysis

3.3.1. Comparison of Temperature Response Curves

To examine the influence of different PID parameter settings on temperature control performance, the outlet water temperature of each version was recorded under the same experimental conditions, and the corresponding temperature response curves were plotted for comparison. The Comparison of Outlet Water Temperature Responses for Different PID Versions is shown in Figure 4.

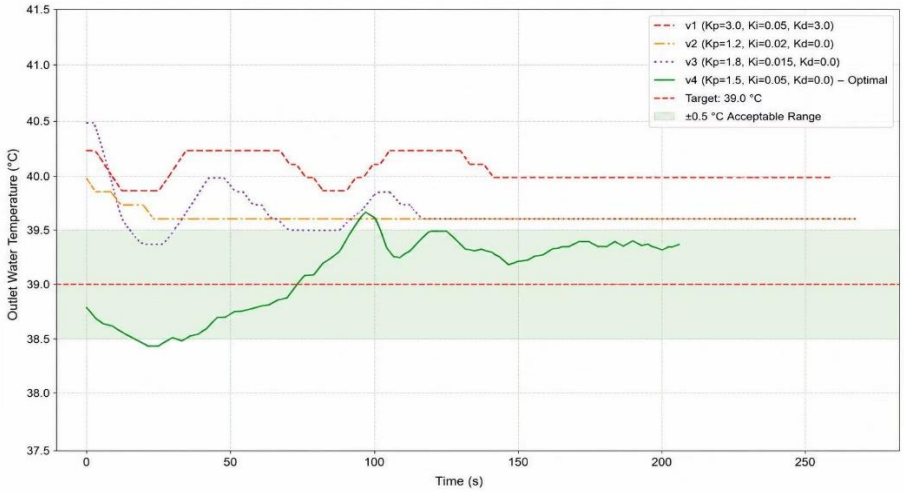


Fig 4. Comparison of Outlet Water Temperature Responses for Different PID Versions.

The temperature response curves show that PID parameter settings have a clear influence on response speed, overshoot, and steady-state error. In v1, the large values of K_p and K_d produced a rapid response; however, the maximum temperature reached 40.19°C, producing an overshoot of 1.19°C. The final stabilized temperature remained above the target temperature of 39°C, indicating a relatively large steady-state error. In v2, K_p was reduced and the derivative term was removed. The overshoot decreased to 0.94°C, but the system eventually stabilized at about 39.56°C and still showed a noticeable steady-state error. In v3, increasing K_p to 1.8 improved the response speed, but the maximum temperature increased to 40.44°C, and the overshoot reached 1.44°C. By contrast, v4, with K_p = 1.5, K_i = 0.05, and K_d = 0, the system maintained a relatively fast response while keeping the overshoot at only 0.69°C. The outlet temperature finally stabilized within the range of 39.13°C–39.38°C, which was the smallest steady-state error among all tested configurations. Based on these results, v4 showed the best overall control performance.

3.3.2. Comparison of Valve Control Behavior

To examine the effect of different PID parameters on actuator control behaviour, the valve opening changes during each experiment were recorded and plotted for comparison. The Comparison of Outlet Water Temperature and Valve Angle under Different PID Parameter Settings is shown in Figure 5.

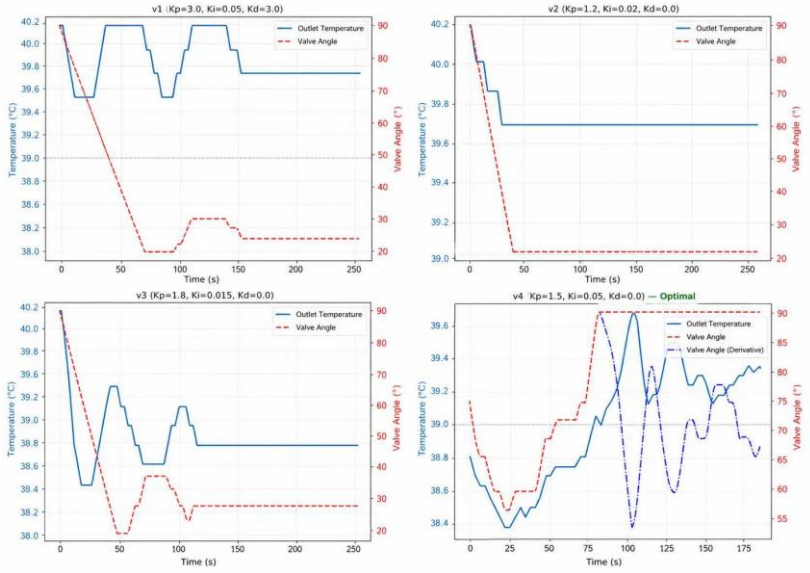


Fig 5. Comparison of Outlet Water Temperature and Valve Angle under Different PID Parameter Settings.

The valve opening curves show a close relationship between valve control behaviour and temperature regulation performance. In v1, the hot water valve quickly moved from 90° to 21° and continued to oscillate afterward. This control behaviour led to significant overshoot and instability. In v2, the hot water valve stabilized relatively early at about 57°. This reduced oscillations, but the limited adjustment range still caused a noticeable steady-state error. In v3, the hot water valve fluctuated frequently between 42° and 51°, which showed that the system was highly sensitive to temperature changes. This behaviour caused temperature oscillations and reduced system stability. In v4, both the hot and cold water valves were adjusted smoothly and continuously. The coordinated movement of the two valves helped balance response speed, overshoot, and steady-state error, giving the best overall control performance among all tested configurations.

3.3.3. Analysis of the Optimal v4 Control Process

Since Version 4 showed the best overall control performance, its control process was chosen for further analysis of temperature regulation and valve operation. The Detailed Control Process Analysis of the Optimal PID Configuration (v4) is shown in Figure 6.

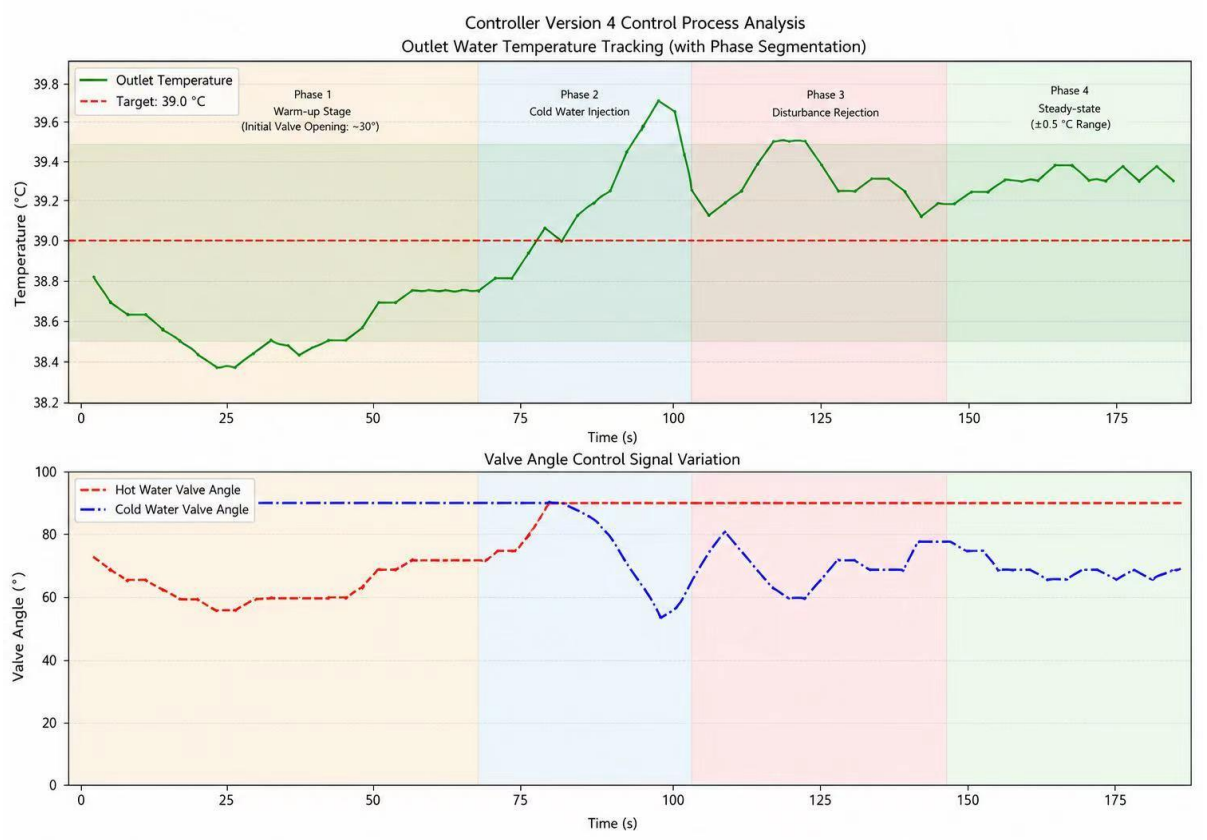


Fig. 6. Detailed Control Process Analysis of the Optimal PID Configuration (v4)

According to the experimental results, the temperature regulation process of v4 can be divided into four stages. In the Heating Stage (0–61 s), the hot water valve gradually moved from 75° to 90° (fully closed), while the cold water valve remained at 90° (fully closed). During this stage, the outlet temperature increased from 38.81°C to 39.06°C. In the Transition Stage (61–102 s), the hot water valve remained fully closed at 90°, while the cold water valve gradually opened from 90° to 54°. The outlet temperature increased from 39.06°C to 39.69°C, creating a slight overshoot. In the Correction Stage (102–150 s), the cold water valve gradually closed from 54° to 69°, while the hot water valve remained at 90°. The outlet temperature decreased from 39.69°C to 39.25°C. In the Steady-State Stage (150–189 s), the outlet temperature fluctuated slightly within the range of 39.13°C–39.38°C, with a variation of about ±0.13°C. During this stage, the valve openings were adjusted between 66° and 78°, showing that the system had reached a stable operating condition.

3.4. Experimental Summary

Four PID parameter configurations were tested to compare their effects on response speed, overshoot, and steady-state error. The results indicate that although v1 achieved a rapid response, the large values of K_p and K_d caused significant overshoot and valve oscillations. In v2, the control gain was reduced, which improved system stability. The steady-state error remained relatively large because the control action was not strong enough. In v3, increasing K_p improved the response speed, but larger temperature fluctuations and overshoot were also observed. The relatively small integral gain (K_i = 0.015) caused slow error accumulation and delayed removal of steady-state error. Among all configurations, v4 (K_p = 1.5, K_i = 0.05, K_d = 0) provided the best balance between response speed, overshoot, and steady-state accuracy. The outlet temperature remained within the range of 39.13°C–39.38°C, with a fluctuation amplitude of about ±0.13°C.

The experimental results also show that the derivative term did not have a major effect on system performance. Because thermal processes respond relatively slowly, the derivative term tended to amplify measurement noise and cause unnecessary valve movements, which increased system oscillations. A controller using only proportional and integral actions showed better overall performance. Based on these results, the optimal controller configuration can be regarded as a PI control strategy, although it was developed within the overall PID control framework.

4. Conclusion

This study investigated temperature fluctuations in domestic hot water supply systems in intelligent buildings and developed a temperature regulation system based on an Arduino controller and a PID control algorithm. The system includes temperature sensing, control, and valve actuation modules. These modules work together to adjust the mixing ratio of hot and cold water according to changes in outlet water temperature and keep the water temperature close to the target value. Experimental results from the prototype showed that the system reduced temperature fluctuations and improved temperature control accuracy. The results also indicate that the proposed system can be used effectively for hot water temperature regulation.

During the study, different PID parameter combinations were tested and compared. The results indicated that controller parameter selection has a significant impact on system performance. For hot water systems with noticeable thermal inertia, excessively high control gains tend to cause temperature oscillations, whereas appropriate proportional and integral actions can achieve a good balance between response speed and control stability. Furthermore, it was observed that the derivative term contributed little to the current system and could amplify measurement noise while increasing unnecessary valve movements. Therefore, PI control was found to be sufficient for achieving the desired control performance.

Although the proposed system demonstrated effective temperature regulation, several limitations remain. The experimental platform was a simplified prototype that did not consider factors such as supply pressure fluctuations, varying user demand, or multi-user water consumption, which may affect performance in real building environments. In addition, the controller employed fixed PID parameters that may not remain optimal under changing operating conditions. Future work could focus on testing the system in more realistic intelligent building scenarios and incorporating adaptive control strategies to improve robustness and adaptability. These improvements would further enhance the practical applicability of the system in domestic hot water supply networks.

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