

DESIGN OF FEEDWATER HEATER TEMPERATURE CONTROL SYSTEM USING PLC-BASED PID-PSO CONTROL

M. Ibrahim Nur Hidayatullah^{1*}, Daeng Rahmatullah², Aditya Chandra Hermawan³, As'ad Shidqy Aziz⁴
^{1*, 2, 3, 4}State University of Surabaya



ABSTRACT

Keywords:

Feedwater Heater
PID
PSO
PLC
Temperature Control

Temperature control in a feedwater heater system is essential for maintaining stability and efficiency in water heating processes, yet conventional systems without control tend to produce uncontrolled temperature oscillations. This study aims to design and implement a temperature control system for a feedwater heater using PID control tuned with the Particle Swarm Optimization (PSO) method based on a Haiwell PLC. Optimal PID parameters were obtained through PSO simulation on a transfer function model derived from open-loop testing using ITAE as the objective function, resulting in parameters $K_p=600$, $K_i=1.345$, $K_d=200$ with a 30-particle configuration. Testing was conducted by comparing three conditions: without PID, PID with trial and error tuning, and PID-PSO, using 18 liters of water across setpoints of 40°C, 50°C, and 60°C. Results show that PID-PSO achieved the best performance with overshoot below 2% and steady-state errors of 0.2°C, 0.15°C, and 0.1°C at each respective setpoint, outperforming both the non-PID and trial and error methods. This study proves that the combination of PID control and PSO tuning is effective for temperature control of a PLC-based feedwater heater system.

INTRODUCTION

Temperature regulation is a critical requirement in many industrial heating processes, including the feedwater heater is a pre-heating device used to raise water temperature before it enters subsequent processes such as boilers, steam systems, or heat-exchange units. At laboratory scale, a feedwater heater is typically operated at a relatively low temperature of around 60°C, since it does not require the high pressures found in industrial-scale systems (Prasetya et al., 2021). Although the process appears simple, precise temperature control is still required to avoid overshoot, fluctuation, and process instability. Conventional on/off control is still widely used, but it produces coarse temperature rises, large oscillations around the setpoint, and a thermal response that is difficult to stabilize. Proportional-Integral-Derivative (PID) control is widely applied to reduce error, smooth temperature changes, and accelerate setpoint tracking (Rahmadini et al., 2023), and when implemented on a PLC such as the Haiwell AT12MOT used in this study, PID control can run reliably in real time. However, PID performance strongly depends on the selection of the K_p , K_i , and K_d parameters. Conventional tuning methods such as trial and error or Ziegler-Nichols often yield suboptimal responses, particularly for thermal systems with slow dynamics. Particle Swarm Optimization (PSO), a population-based metaheuristic that mimics the foraging behaviour of bird flocks, has been shown to improve PID performance in other dynamic systems, such as DC motor speed control, where it produced faster responses, negligible overshoot, and a steady-state error below 5% even under varying load. PSO has also been reported to yield more stable and consistent PID parameters than manual tuning, with faster rise time and shorter settling time (Rahayu et al., 2022). These successes motivate the application of PSO-based tuning to water-heating systems, which are generally non-linear and slow-

responding. Building on this need, this study focuses on the design and implementation of a temperature control system for a feedwater heater using PID control tuned with PSO on a Haiwell PLC and HMI, and compares the resulting response against a system without a controller and a PID tuned by trial and error

RESEARCH METHOD

A. Research Design

This study used an experimental research method to design, implement, and evaluate a PLC-based feedwater heater temperature control system using PID-PSO control. The research stages consisted of hardware design, software/PID-PSO programming, and overall system testing. Testing was carried out on a laboratory-scale prototype using 18 litres of water, comparing three control conditions without a controller (Non-PID), PID tuned by trial and error, and PID tuned with PSO at setpoints of 40°C, 50°C, and 60°C. System responses were analysed using rise time, peak time, overshoot, settling time, and steady-state error as the primary performance indicators.

B. System Architecture

The proposed system consists of a Haiwell AT12MOT PLC as the main controller, a Haiwell A16XDR digital expansion module and a Haiwell A04AI analog module, an RTD PT100 temperature sensor with a 4–20 mA transmitter, two 400 W electric heaters actuated through LY2N 24 VDC relays, and a Haiwell C7S-W HMI for setpoint entry and real-time monitoring. Power is supplied through a 2-pole MCB, which protects the system against overcurrent and short-circuit conditions (Gading et al., 2020). The PLC reads the actual water temperature from the PT100 sensor (Li H., 2024), computes the PID control action, and drives the heaters through the relays, while the HMI allows the operator to set the target temperature and observe the temperature response in real time. PID parameters obtained offline through PSO tuning in MATLAB are downloaded into the PLC prior to testing. Figure 1. shown the wiring and system architecture of the plant.

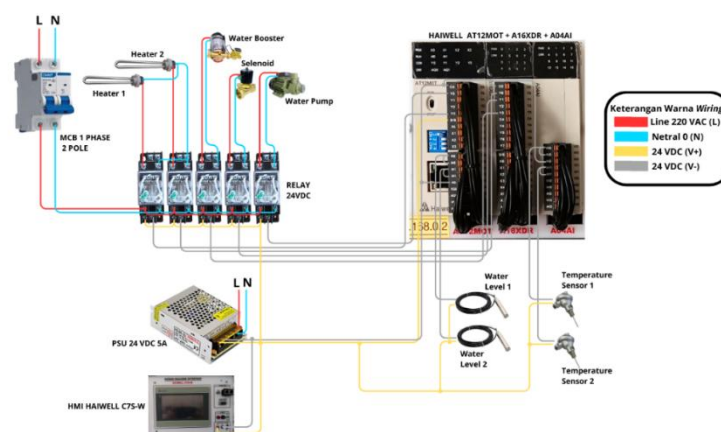


Figure 1. Wiring and system architecture of the PLC-based feedwater heater temperature control system

The plant transfer function was first identified from open-loop step-response testing, in which the heater was driven with a fixed input while the resulting water temperature rise was recorded. From this test, a first-order model was obtained relating the change in water temperature to the change in heater input, together with the time constant of the thermal response. This transfer function was then used as the basis for offline PID tuning in MATLAB using Particle Swarm Optimization with an Integral of Time-weighted Absolute Error (ITAE) objective function, chosen for its sensitivity to long-term error and its tendency to produce a smooth, quickly-settling response.

PSO searches for the combination of K_p , K_i , and K_d that minimizes the ITAE cost by iteratively updating a population of candidate solutions (particles) based on each particle's personal best position and the swarm's global best position. Particle-count configurations of 10, 20, 30, 40, and 50 were compared, each run five times; the 30-particle configuration produced the lowest best cost together with the smallest overshoot, and was therefore selected. The resulting parameters $K_p = 600$, $K_i = 1.345$, and $K_d = 200$ were then implemented in the PID block on the Haiwell PLC, as illustrated in the control block diagram in Figure 2.

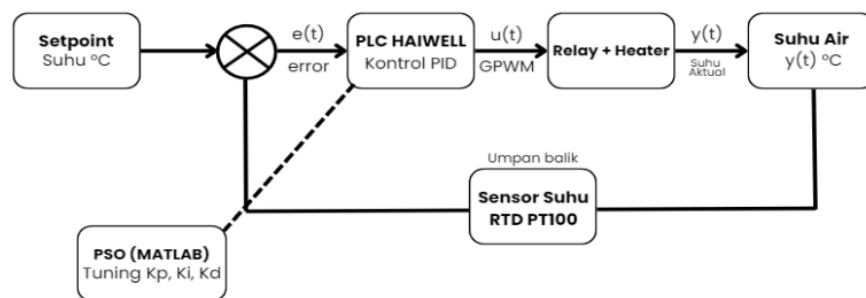


Figure 2. Block diagram of the PID-PSO feedwater heater temperature control system.

System testing was performed under two main conditions: without a PID controller, to obtain the natural response characteristics of the heating process, and with PID-PSO control, to evaluate the resulting performance improvement a PID tuned by trial and error was included as an additional comparison. Test data were analysed in terms of rise time, overshoot, settling time, and steady-state error, with steady-state error computed as the absolute difference between the setpoint and the average midpoint of the temperature oscillation once the response reached a relatively constant state.

RESULTS AND DISCUSSION

A. PSO Tuning

Open-loop testing showed the water temperature rising from an initial 30°C toward 40°C, from which a first-order transfer function was derived. PSO tuning of this model using the ITAE objective function, with a 30-particle configuration, produced a best cost (ITAE) of 55,553.705 together with a near-zero simulated overshoot and steady-state error. When the resulting parameters ($K_p = 600$, $K_i = 1.345$, $K_d = 200$) were implemented on the real plant, the actual response reached its first overshoot of 0.8°C at 883 seconds and settled

more slowly than the simulation predicted, with rise time and settling time roughly 3.7 and 13.9 times longer, respectively. This gap is attributed to the simplified first-order model not fully capturing the plant's non-linear heat distribution, dead time, and heat loss, as well as to the non-ideal, relay-based PWM actuation and environmental disturbances present in the real laboratory setting.

B. Testing at Various Setpoints

At each setpoint, the temperature response of the Non-PID, PID trial-and-error, and PID-PSO systems was recorded for 18 litres of water, and rise time, peak time, overshoot, settling time, and steady-state error were computed for each. Figure 3 shows the comparative response of the three control methods at the 40°C setpoint. Figure 4 shows the comparative response of the three control methods at the 50°C setpoint. Figure 5 shows the comparative response of the three control methods at the 60°C setpoint.

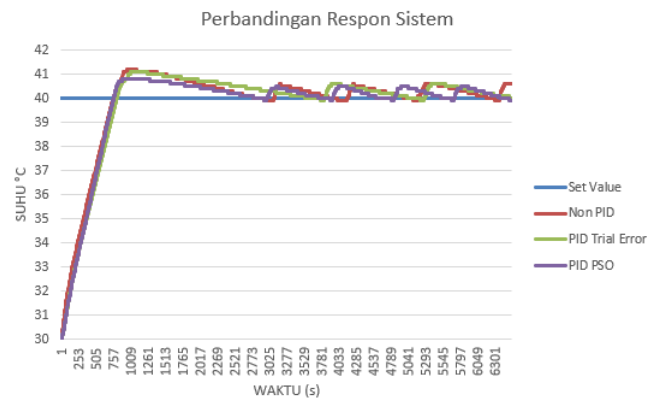


Figure 3. Temperature response of Non-PID, PID Trial and error, and PID-PSO control at setpoint 40°C.

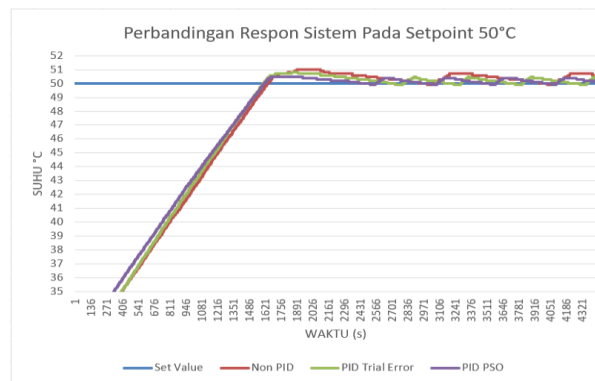


Figure 4. Temperature response of Non-PID, PID Trial and error, and PID-PSO control at setpoint 50°C.

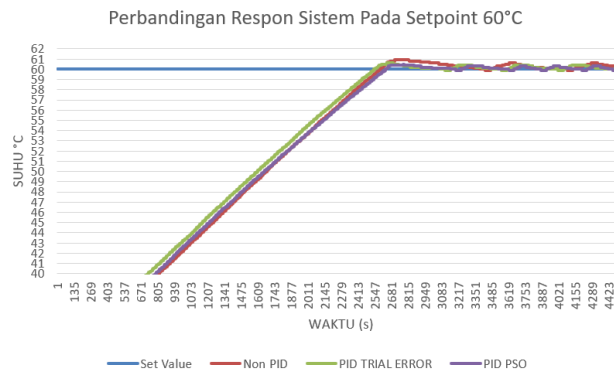


Figure 5. Temperature response of Non-PID, PID Trial and error, and PID-PSO control at setpoint 60°C.

At the 40°C setpoint, PID-PSO achieved the best performance across all indicators, with the fastest rise time (601 s), the smallest overshoot (0.8°C, 2.0%), the fastest settling time (3,110 s), and the smallest steady-state error (0.2°C), compared with 0.25°C for both the Non-PID and trial-and-error systems. At the 50°C setpoint, PID-PSO no longer had the fastest rise time (1,321 s, versus 1,304 s for Non-PID and 1,266 s for trial-and-error PID), but it remained the best in overshoot (0.5°C, 1.0%), settling time (2,630 s), and steady-state error (0.15°C, versus 0.2°C and 0.3°C respectively). The same trade-off appeared at the 60°C setpoint: rise time for PID-PSO (2,102 s) was slightly slower than the other two methods, yet PID-PSO still produced the smallest overshoot (0.5°C, 0.83%) and the smallest steady-state error (0.1°C, versus 0.15°C and 0.25°C). This outcome is attributed to the parameters $K_p=600$, $K_i=1$, and $K_d=200$ remaining unchanged from the 40°C setpoint configuration, without retuning. At higher setpoints, the temperature differential the system must bridge is greater, resulting in a faster initial rate of temperature change. The $K_d=200$ setting reacts early to this rate of change, triggering damping action sooner and slightly slowing the PID-PSO rise time. However, this initial damping prevents a significant temperature spike, keeping overshoot minimal and allowing the system to reach a steady state more quickly with the lowest final error. In other words, the PID-PSO system slightly sacrifices initial speed to achieve a more stable and precise response.

C. Comparison of Elctrical Energy Consumption

Cumulative energy consumption of the PID trial-and-error and PID-PSO systems was measured while heating 18 litres of water from 30°C to 40°C, a process lasting approximately 13 minutes. Table 1 presents the accumulated energy (in watt-hours) recorded at each 1°C increase.

Table 1. Energy consumption of the PID trial-and-error and PID-PSO at setpoint 40°C

No	Suhu (°C)	PID Trial Error (Watt-hour)	PID-PSO (Watt-hour)
1	30	0,002	0,005
2	31	0,018	0,015
3	32	0,040	0,032
4	33	0,061	0,049
5	34	0,080	0,068
6	35	0,101	0,087
7	36	0,122	0,105
8	37	0,145	0,125
9	38	0,167	0,146
10	39	0,189	0,166
11	40	0,214	0,187

At the very start of the process, PID-PSO consumed slightly more energy than the trial-and-error PID (0.005 Wh versus 0.002 Wh) because its higher gain produced a more aggressive initial control action to accelerate setpoint tracking. From 31°C onward, however, PID-PSO consistently consumed less cumulative energy. By the end of the test, at 40°C, PID-PSO had consumed a total of 0.187 Wh, which is 0.027 Wh (12.6%) lower than the 0.214 Wh consumed by the trial-and-error PID. This efficiency gain is consistent with PID-PSO's smaller overshoot and steady-state error, since fewer or smaller corrective actions are required to counter temperature overshoot, reducing the energy wasted through repeated heating/cooling correction.

CONCLUSION

The PLC-based PID-PSO feedwater heater temperature control system developed in this study was able to maintain water temperature closer to the setpoint than either a system without a controller or a PID tuned by trial and error, producing the smallest steady-state error at every tested setpoint (0.2°C, 0.15°C, and 0.1°C at 40°C, 50°C, and 60°C, respectively). The system also showed consistent behaviour across setpoint variations in terms of accuracy and stability always producing the smallest overshoot and steady-state error although its advantage in transient speed (rise time and settling time) was not consistent, since the ITAE objective function used in PSO tuning emphasizes minimizing cumulative error over time rather than the speed of the initial response. In addition, PID-PSO consumed 12.6% less cumulative energy than the trial-and-error PID during a 30°C-to-40°C heating cycle, despite a slightly higher initial power draw from its more aggressive control action. Overall, these results demonstrate that combining PID control with PSO-based offline tuning is an effective and energy-efficient approach for PLC-based feedwater heater temperature control, and this work provides a practical basis for further development for example, using a more accurate transfer-function model and

higher-capacity, better-placed heating elements to achieve faster and more uniform temperature distribution.

ACKNOWLEDGEMENTS

The author would like to express sincere gratitude to the Department of Electrical Engineering, Faculty of Vocational Studies, State University of Surabaya, for the academic guidance, laboratory facilities, and technical support provided throughout this research. Special appreciation is extended to the supervisors, examiners, and laboratory staff whose valuable suggestions and assistance contributed significantly to the completion of this work.

REFERENCES

- Gading Primadhika, D., Parjiman, Mochammad, D., & Firdaus, H. (2020). PERUBAHAN SUHU LINGKUNGAN TERHADAP WAKTU TRIP PADA MINI CIRCUIT BREAKER 6A TIPE C. *Journal of Electrical Vocational Education and Technology*, 5(1), 6–13. <https://doi.org/10.21009/jevet.0051.02>
- Li, H. (2024). Pt100 temperature measurement sensors design and transducer simulation. *Journal of Physics: Conference Series*, 2897(1), 12011. <https://doi.org/10.1088/1742-6596/2897/1/012011>
- Prasetya, S. D., Budi, E. S., & Yulianto, Y. (2021). Aplikasi PID Controller Level Feed Water Boiler pada Miniplant dengan Menggunakan PLC Dan HMI. *Jurnal Elektronika Dan Otomasi Industri*, 7(3), 32. <https://doi.org/10.33795/elkolind.v7i3.206>
- Rahayu, E. S., Ma'arif, A., & Çakan, A. (2022). Particle Swarm Optimization (PSO) Tuning of PID Control on DC Motor. *International Journal of Robotics and Control Systems*, 2(2), 435–447. <https://doi.org/10.31763/ijrcs.v2i2.476>
- Rahmadini, V. F., Ma'arif, A., & Abu, N. S. (2023). Design of Water Heater Temperature Control System using PID Control. *Control Systems and Optimization Letters*, 1(2), 111–117. <https://doi.org/10.59247/csol.v1i2.41>
- Setiawan, J., Abdurahman, A., Sunardi, S., Sugeng, S., & Syukur, A. M. (2022). DESIGN OF PLC BASED TEMPERATURE CONTROL SYSTEM FOR FOOD STABILITY TEST CHAMBER. *Sebatik*, 26(2), 482–488. <https://doi.org/10.46984/sebatik.v26i2.1968>