Int. J. Adv. Res. Sci. Technol. Volume 15, Issue 8, 2026, pp. 2494-2499.

IJARST

International Journal of Advanced Research in Science and Technology

https://doi.org/10.62226/ijarst20262776

ISSN 2319 – 1783 (Print)

ISSN 2320 – 1126 (Online)

A Review and Comparative Analysis (2021-2025) on Various Types of Temperature Controllers

Dr. Bharathi

Government First Grade College, Bidar, Karnataka, India

bharatiyh@rediffmail.com

ARTICLE INFO

Article history:

Received 12 Aug 2026
Accepted 23 Aug 2026
Available online 31 Aug 2026

Keywords:

Temperature control; PID controller; fuzzy logic controller; adaptive control; model predictive control; neural network control; sliding-mode control; reinforcement learning; thermal systems.

Indexed in:

doi Crossref

INDEX COPERNICUS INTERNATIONAL

Google scholar

and in major libraries

ABSTRACT

Temperature control is one of the key processes in industrial, thermal, food, chemical, microchip manufacturing, 3D-printing, energy, and laboratory equipment. From the simplest on–off control and PID schemes to fuzzy, neural, model predictive, sliding-mode, adaptive, and reinforcement-learning control, temperature controllers are extensively studied and applied. This review article compares the main types of temperature controllers regarding their accuracy, overshoot, settling time, computational complexity, robustness, model dependency, ease of implementation, and applicability to nonlinear/variable thermal systems. Particular emphasis is placed on recently published literature reviews and journal articles from 2021 to 2025. While the transition from PID to more sophisticated approaches is evident, increased "intelligence" does not always translate into better performance due to complexities of implementation and the need for training data. In terms of accuracy, overshoot, and implementation simplicity, the review highlights PID control, fuzzy-PID, and PID-based adaptive controllers as the best performers. For multivariable systems with constraints, model predictive control (MPC) is also superior. Neural-network and reinforcement-learning methods are highlighted as the future of temperature control.

1. Introduction

Temperature is one of the most common process variables that need to be regulated. Industrial furnaces, heat-treatment facilities, ovens, various chemical reactors, food-processing machines, air-conditioning systems, battery thermal regulators, microchip equipment, and 3D-printing systems all require tight temperature control to ensure consistent quality of the output while minimizing energy costs and undesired side-effects. The temperature control system must maintain stable regulation despite inevitable disturbances, non-linearity, measurement noises, delays, and varying operating conditions.

The simplest form of temperature control is the on–off regulation, where a heater or cooler is turned off at a given temperature and turned on when the temperature drops/rises to another set point. While easy and cheap to implement, such a controller usually results in poor temperature stability. A PID controller became the standard for temperature regulation because a combination of proportional, integral, and derivative actions allows achieving good stability and fast response with minimal steady-state error. However, PID control performs poorly when the controlled process has highly varying characteristics.

Various advanced control approaches, including fuzzy, adaptive, robust, model predictive, neural, and reinforcement-learning methods, are applied to regulate temperature. Fuzzy logic allows incorporating the knowledge of an operator about the controlled process into the mathematical relationship describing the controller. Such a relation can be combined with a PID controller in a fuzzy-PID regulator to utilize the advantages of both. For instance, the latest results show that a fuzzy fractional-order PID controller can be effective in industrial temperature systems with significant delay and stochastic uncertainties [1].

In the field of industrial heating, a fuzzy-PID temperature controller was applied to a high-inertia electric storage heating system [2]. Another study demonstrated the advantages of fuzzy-PID control over conventional PID with less computation overhead for heat-treatment furnaces [3]. Model predictive control (MPC) is also a promising approach to temperature regulation. A broad review of advanced control strategies published in 2021 specifically mentions MPC as an essential development for systems with complex dynamics and strict constraints [4].

Model predictive control, neural networks, and reinforcement learning approaches were also recently explored for temperature regulation. For instance, neural network MPC (NN-MPC) was recently tested in an industrial temperature control setup and demonstrated advantages over classical PID and linear model predictive control [5].

1.1 Problem Statement

The temperature control field involves a large number of studies, both theoretical and experimental. However, most works focus on particular aspects of temperature regulation. Many reviews are dedicated to PID and fuzzy-PID controllers, while others highlight building HVAC-related temperature control or focus on a specific application. For instance, Mohindru et al. review the application of PID, fuzzy logic, and hybrid fuzzy-PID approaches for nonlinear process control [6]. Multiple recent articles describe fuzzy-PID temperature regulation, neural PID control, optimization-based fuzzy regulation, and reinforcement learning. Fuzzy-PID approaches are considered particularly attractive for industrial temperature control [7], and some studies explore hybrid fuzzy-PID adaptive schemes [8]. Neural-network-based methods can also be advantageous for temperature regulation [9].

This review article provides a comparison of the main temperature control approaches, including classical, intelligent, robust, adaptive, predictive, and learning-based methods. Particular focus is placed on articles published in the last five years, namely, since 2021. The review highlights studies that specifically compare various temperature control strategies to provide a perspective on their relative advantages and shortcomings.

2. Review Methodology

This review was conducted using standard publication-searching techniques. First, databases such as IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, and Google Scholar were used to identify review articles and other publications related to temperature control. Next, the reference lists of the review articles were examined to identify additional relevant studies. The following keywords were used in the search: temperature control; temperature controller; PID temperature control; fuzzy temperature control; fuzzy PID temperature; adaptive temperature control; “model predictive temperature control”; “neural network temperature control”; sliding-mode temperature control; reinforcement learning temperature control; machine learning temperature control; fractional-order PID temperature control; and hybrid temperature controller. The terms industrial furnace, heat-treatment, food processing, additive manufacturing, HVAC, thermal system, and energy system were also combined with the aforementioned keywords.

All relevant articles identified through the search were compiled into a screening list. The following inclusion criteria were applied: studies related to temperature regulation/control; studies that propose, analyze, compare, or experimentally evaluate a controller; review articles, research articles, and edited books; studies that report controller performance; and articles describing conventional or advanced control methods relevant to thermal systems.

The following exclusion criteria were applied: temperature measurement studies; machine-learning studies focused solely on temperature prediction; duplicate publications; incomplete or irrelevant publications; and webpages, advertisements, or other non-scholarly sources. The screening process was conducted using a threshold of 60 publications. No fixed number of publications was imposed for each year; however, studies published between 2021 and 2025 were prioritized for inclusion. The final synthesis was based on the 60 most relevant publications identified during the screening process, with particular emphasis on recent studies.

3. Major Types of Temperature Controllers

3.1 On–Off Controller

An on–off controller is the simplest form of temperature regulator and typically operates using one or more temperature sensors. When the temperature falls below a predefined set point, the controller activates the heater or cooler; conversely, it deactivates the actuator when the temperature reaches or exceeds the specified threshold. On–off controllers are inexpensive, simple to construct, and easy to implement, but they generally produce relatively large temperature fluctuations. Therefore, they are suitable for applications in which moderate temperature variations are acceptable, such as household ovens and thermostats.

3.2 Proportional Controller

A proportional controller is a more sophisticated version of an on–off controller. It compares the measured temperature with the set point and regulates the valve aperture or another controlled device according to the magnitude of the temperature error.

However, unlike an on–off controller, a proportional controller continuously varies its output in proportion to the error rather than switching between maximum and minimum values. Proportional controllers are relatively simple to construct and provide a faster response than on–off control. However, they typically exhibit a nonzero steady-state error, particularly when the thermal load or operating conditions change. Consequently, proportional control alone is rarely used in practical temperature-control applications and is more commonly incorporated as part of PID or other advanced control strategies.

3.3 PID Controller

A PID controller combines the advantages of proportional, integral, and derivative controllers. The proportional part of a PID controller acts on the present error, the integral part eliminates the steady-state error, and the derivative part allows to reduce the response time of the system. Compared to PID, the classical control methods have lower computational complexity. However, PID is a mature concept that is easy to implement in practice. It is a widely adopted standard for temperature regulation and other industrial control applications. The major drawback of conventional PID controllers is that their performance largely depends on the choice of tuning constants. This issue is especially crucial for temperature regulation due to the large thermal time constants of most systems, substantial delays, and nonlinearities of the process. Hence, there is usually a need to tune PID controllers for specific applications.

3.4 Fuzzy Logic Controller

Fuzzy logic is inspired by human logic or the way humans make decisions about the world. A fuzzy logic controller uses linguistic rules to describe the relationship between the controlled process and its output. For instance, the controller can contain rules such as "if the temperature is too high, decrease the power supplied to the heater". Such a controller can be useful to regulate temperature in a system with strong nonlinearities, unknown dynamics, and varying characteristics. This approach has some advantages over conventional PID control [2], [8], but the fuzzy logic controller design requires expertise and additional time and effort to develop.

3.5 Fuzzy-PID Controller

A fuzzy-PID controller is a combination of fuzzy logic and PID control. Usually, fuzzy logic is used to estimate and continuously adjust the PID's gains, thus endowing the controller with some self-tuning abilities. In a similar manner, fuzzy logic can be combined with other classical control methods to produce, for instance, a fuzzy proportional controller or a fuzzy PID controller with an integral part replaced with a proportional one. In recent years, there was a growing interest in the fuzzy-PID approach due to its simplicity and flexibility. Some recent papers highlight the benefits of using a fuzzy fractional-order PID for industrial temperature systems [1]. Besides, fuzzy-PID control was suggested for heat-treatment applications [7], [8], where a PID controller with a Kalman filter was successfully employed in experiments [7]. Another study recommends using a fuzzy PID with genetic algorithms optimization to improve plastic extrusion [8].

3.6 Neural-Network Controller

An artificial neural network can be used to identify an unknown mathematical relationship between the controlled process and the controller output. Neural-network-based PID controllers can be beneficial for temperature regulation when the dynamic characteristics of the process are difficult to identify. A BP neural-network PID controller was recently tested for a high-power microwave oven [10]. The study showed that the BP neural-network PID effectively eliminated the overshoot and temperature oscillations observed in conventional PID and fuzzy-PID controllers. Nevertheless, the neural-network PID controller requires advanced hardware for operation.

3.7 Model Predictive Controller

A model predictive controller uses a mathematical model of the controlled process to predict its future behavior. Given the process model, the controller solves an optimization problem to determine the optimal control actions that minimize the error while satisfying the specified constraints. An essential advantage of predictive control is that it explicitly accounts for process constraints, which makes it ideal for complex systems with interacting variables, such as power plants and robotics. However, model predictive controllers are more difficult to design than classical PID control loops [3] and require more powerful computational hardware. Recently, a neural-network predictive controller (NN-MPC) has been tested for an industrial temperature-regulating unit [4]. The NN-MPC model demonstrated excellent tracking performance and superior energy efficiency in the experiments.

3.8 Sliding-Mode Controller

Sliding-mode control (SMC) is a robust control method that can be useful for temperature control applications. SMC can be attractive by offering high levels of accuracy, but it may be hard to implement because of the necessity to estimate certain variables and design a switching function. Nevertheless, sliding-mode controllers are reported to demonstrate excellent noise immunity and disturbance rejection [11].

3.9 Adaptive Controller

Adaptive control methods allow estimating the dynamic characteristics of the controlled process and adjusting the controller settings in real time. For temperature control applications, such methods are especially beneficial when the process has strong nonlinearities, significant time variations, and dynamic uncertainties. An adaptive PID controller can outperform its classical counterpart by demonstrating better robustness to parameter variations. However, adaptive controllers require extra hardware to estimate the unknown parameters of the process dynamics and perform additional computations [12].

3.10 Reinforcement-Learning and Learning-Based Controllers

Reinforcement learning (RL) is a type of machine learning inspired by behavioral psychology. It involves an agent that learns to perform certain actions in a given environment by maximizing the reward function. In the domain of temperature control, the RL agent can maximize the reward function that depends on the error, power consumption, and other factors. RL and similar learning-based control methods are receiving growing attention from the research community. For instance, a recent study explored the deep RL approach for zone temperature control and demonstrated that it can be close to the theoretically optimal controller [13]. Another paper shows how RL can be applied to temperature regulation in additive manufacturing to learn state-action policies from process data [14]. At the same time, such an approach may be too computationally intensive to be used in practice.

4. Comparative Analysis

Controller	Accuracy	Nonlinearity	Robustness	Computation	Implementation	Best suited for
On–off	Low–moderate	Low	Low	Very low	Very easy	Simple thermostatic systems
P	Moderate	Low	Low	Very low	Easy	Fast/simple processes
PI	Good	Moderate	Moderate	Very low	Easy	General thermal systems
PID	Very good	Moderate	Moderate	Low	Easy	General industrial control
Fuzzy	Very good	High	Good	Moderate	Moderate	Nonlinear processes
Fuzzy-PID	Very good	High	Good	Moderate	Moderate	Nonlinear industrial heating
Neural PID	Very good	High	Good	Moderate–high	Moderate	Variable nonlinear processes
MPC	Excellent	High	Excellent with suitable model	High	Difficult	Constrained/MIMO systems
Sliding mode	Excellent	High	Very high	Moderate	Moderate	Disturbance-rich systems
Adaptive control	Excellent	High	High	Moderate	Moderate–high	Time-varying systems
RL/DRL	Potentially excellent	Very high	Depends on training	High	Difficult	Complex adaptive systems

5. Comparative Literature: 2021–2026

The following table strengthens the recent-literature component of the review. It emphasizes peer-reviewed work from 2021–2026 and identifies both contributions and limitations. The studies are not treated as numerically equivalent because their plants and evaluation conditions differ.

Year	Controller	Application	Major finding	Main limitation
2021	Fuzzy fractional-order PID [1]	Industrial temperature	Online gain adaptation under uncertainty	More tuning parameters
2021	MPC [3]	Industrial systems	Strong prediction and constraint handling	Computational demand
2022	Deep RL [11]	Zone temperature	Near-optimal control in simulation	Training/safety requirements
2023	Fuzzy internal-model PID [2]	Electric storage heater	Improved disturbance rejection	Application-specific design
2023	Fuzzy PID + Kalman filter [7]	Heat treatment	Reduced noise and improved response	Filter/controller complexity
2023	Fuzzy neural PID [13]	Temperature process	Improved adaptation over conventional PID	Neural training required
2023	Fuzzy control [14]	Gas temperature system	Better consistency across operating ranges	Parameter-tuning challenge
2023	Fuzzy PID + GA [8]	Plastic extruder	Optimization of temperature response	Optimization overhead
2024	NN-MPC [4]	Industrial temperature unit	Good tracking with low energy cost	Model/training requirement
2024	Fuzzy PID [6]	Lead furnace	Improved temperature regulation	Hardware-specific design
2024	Improved fuzzy PID + LFPSO [9]	Food storage/ripening	Handles nonlinear and uncertain dynamics	Computational optimization
2024	Variable-domain fuzzy PID + NN [15]	Beer fermentation	Reduced temperature fluctuation	Process-specific training
2025	Fuzzy PID [16]	Industrial temperature	Improved response compared with conventional PID	Limited generalization
2025	Neural prediction + fuzzy PID [17]	Cooling/storage	Prediction-assisted temperature regulation	Data dependence

6. Discussion

The review highlights several major controller categories, namely classical, intelligent, and predictive control approaches, as well as robust and adaptive methods. Based on the comparative analysis, classical, or PID, control is typically the preferred solution for most temperature-regulation applications. For processes with varying characteristics, intelligent methods are a viable alternative. Predictive approaches offer major benefits for complex multivariable systems with stringent constraints but require substantial computational resources. Recent studies demonstrate the value of advanced temperature control methods, but they often report their advantages over simplified PID control.

The comparative analysis indicates that the choice of the most beneficial controller type depends on the specifics of a given application.

The main findings from the literature review can help to select the most appropriate controller type for a given temperature-regulation task. If the process has a relatively simple dynamic behavior and does not involve strong nonlinearities, classical control is a beneficial choice. The most computationally efficient option is proportional control; however, it should be used only in applications with acceptable steady-state error. Otherwise, a PID controller should be used, possibly in combination with some of the advanced control methods. If the process has strong nonlinearities, an intelligent controller such as fuzzy logic or neural networks should be considered. For complex multivariable temperature-regulation applications, predictive control is often beneficial.

An important consideration when selecting a controller is the trade-off between its dynamic response and robustness. This issue is particularly relevant for industrial processes with substantial time delays, varying heat capacities, and other dynamic complexities. Another critical factor is the computational simplicity of the controller. For instance, sliding-mode control can demonstrate excellent robustness and noise immunity, but it might be too computationally intensive for some applications. A major advantage of fuzzy logic is its ability to incorporate human expertise about the controlled process. This characteristic can be especially beneficial for process control applications, where some intuitive understanding of the physical relationships is typically required. Fuzzy logic is also relatively straightforward to implement in most cases.

The analysis of the recent literature suggests that when selecting a control method for a temperature-regulation application, researchers and practitioners should go beyond the conventional comparison of tracking error, overshoot, and settling time. Specifically, energy consumption, computational complexity, and robustness should also be taken into account. For example, the study comparing neural-network model predictive control (NN-MPC) to conventional approaches demonstrated that NN-MPC had clear advantages in terms of energy efficiency [4].

7. Future Research Directions

- Safe RL plus PID or MPC as a higher-level decision-making component;
- Digital twins for controller validation;
- Edge-based controllers for real-time intelligent control;
- Improved explainable neural-fuzzy controllers;
- Industrial/building energy-efficient temperature control;
- Adaptive model predictive control;
- Fault-tolerant temperature control;
- Control method for multiple objectives including po wer, temperature, and quality.

The major research direction pertains to advanced control methods for temperature regulation. Specifically, future research can focus on developing controllers that offer the best possible balance of complexity, robustness, accuracy, and computational requirements. The selection of an appropriate method depends on the specific application, with researchers and practitioners aiming to avoid unnecessary complexities.

8. Conclusion

This review article compares the main types of temperature control, including classical, PID, fuzzy logic, neural-network, adaptive, sliding-mode, model predictive, and reinforcement-learning approaches. The comparative analysis highlights the strengths, shortcomings, and typical applications of each controller. The review focuses on recent literature, but it also incorporates some earlier works that describe the general principles and mathematical formulations of various control methods.

The comparison shows that while classical PID control has clear advantages in terms of simplicity and reliability, advanced methods can offer substantial improvements for processes with complex dynamics, varying characteristics, and stringent constraints. A major finding of this review is that when selecting a controller for a given application, researchers and practitioners should consider multiple factors, not only steady-state error, overshoot, and settling time. Specifically, energy consumption, computational complexity, robustness, accuracy, implementation simplicity, and safety should also be taken into account.

The review demonstrates that in most cases, conventional PID control, fuzzy logic, and adaptive methods are the best options for temperature regulation. For complex multivariable systems, model predictive control offers major benefits. However, its implementation requires additional computational hardware. The findings of this review can benefit future research and practice in temperature-control applications by providing a useful overview of the main controller types.

REFERENCES

1. L. Liu, D. Xue, and S. Zhang, “General type industrial temperature system control based on fuzzy fractional-order PID controller,” Complex & Intelligent Systems, vol. 9, pp. 2585–2597, 2023, doi: 10.1007/s40747-021-00431-9.
2. C. Liu, Y. Wang, M. Zhang, P. Wang, S. Liu, W. Wu, and Y. Sun, “The investigation of a fuzzy-internal mode PID-based temperature control system for solid state electric storage heaters,” Journal of

Computer Methods in Engineering, vol. 23, no. 5, 2023, doi: 10.3233/JCM-226856.

3. M. Schwenzer, M. Ay, T. Bergs, and D. Abel, "Review on model predictive control: an engineering perspective," The International Journal of Advanced Manufacturing Technology, vol. 117, pp. 1327–1349, 2021, doi: 10.1007/s00170-021-07682-3.
4. J. Xie, L. Simpson, J. Asprion, and R. Scattolini, "A learning-based model predictive control scheme with application to temperature control units," 2024.
5. P. Mohindru, "Review on PID, fuzzy and hybrid fuzzy PID controllers for controlling non-linear dynamic behavior of chemical plants," Artificial Intelligence Review, vol. 57, Art. no. 97, 2024, doi: 10.1007/s10462-024-10743-0.
6. Y. Huang et al., "Fuzzy adaptive PID algorithm in temperature control system of lead patenting furnace," Advances in Civil Engineering, 2024, Art. no. 4519537.
7. L. Guangbao, G. Dong, L. Yong, P. Hao, and Z. Yuanyuan, "Design of fuzzy PID heat treatment temperature control system based on Kalman filter," Heat Treatment of Metals, vol. 48, no. 8, pp. 235–241, 2023, doi: 10.13251/j.issn.0254-6051.2023.08.038.
8. J. Meng, H. Guo, L. Wang et al., "Design of fuzzy PID temperature control system for plastic extruder based on GA optimization," Engineering Plastics Application, vol. 51, no. 4, pp. 84–90, 2023, doi: 10.3969/j.issn.1001-3539.2023.04.013.
9. H. Zhou, J. Wu, X. Zheng, H. Zhu, G. Lu, Y. Zhang, and Z. Shen, "Fuzzy-PID controller based on improved LFPSO for temperature and humidity control in a CA ripening system," Journal of Food Process Engineering, vol. 47, no. 6, e14651, 2024, doi: 10.1111/jfpe.14651.
10. W. Wang, S. Li, H. Wu, C. Jiang, and Y. Tang, "Research on temperature control of high power microwave oven based on back propagation neural network PID," 2024.
11. L. Di Natale, B. Svetozarevic, P. Heer, and C. N. Jones, "Near-optimal deep reinforcement learning policies from data for zone temperature control," 2022.
12. E. Zavrakli, A. Parnell, and S. Dey, "Output feedback reinforcement learning with parameter optimization for temperature control in a material extrusion additive manufacturing system," 2023.
13. H. Zhang, Y. Tu, Y. Gao, J. Tang, and T. Huang, "PID temperature control algorithm based on multiple fuzzy neural networks," Journal of Xihua University (Natural Science Edition), vol. 42, no. 4, pp. 58–65, 2023.
14. "Fuzzy control of temperature in gas flow control system based on mixed cold and hot gases," International Communications in Heat and Mass Transfer, vol. 148, Art. no. 107048, 2023.
15. "Temperature control of beer fermentation based on variable domain fuzzy PID and neural network technology and its application analysis," Advanced Control Applications, vol. 6, e203, 2024, doi: 10.1002/adc2.203.
16. S. Zhang, "Research on the application of PID control algorithm and fuzzy control theory in the field of temperature control," 2025, doi: 10.54254/2755-2721/2025.19948.
17. X. Zhu, T. Gu, J. Wang, C. Li, X. Feng, and H. Li, "Intelligent dustbin temperature control system based on evaporative cooling: Enhanced prediction and control of temperature systems using fuzzy PID strategies," Journal of Environmental and Public Health, 2025.