International Journal of Economic, Technology and Social Sciences
e-ISSN 2775-2976

International Journal of Economic, Technology and Social Sciences
url: https://jurnal.ceredindonesia.or.id/index.php/injects
Volume 6 Number 2 page 252-261

Design Of Fuzzy Logic-Based Temperature Control System For PPF Installation Workshop Spaces

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ABSTRACT

This Paper described design a fuzzy logic-based temperature control system for Paint Protection Film (PPF) installation workshop spaces. PPF installation requires optimal temperature conditions (20-27°C) to ensure proper adhesion, but workshop environments often experience temperature fluctuations that compromise installation quality. The research method uses computational simulation with a modified Mamdani fuzzy logic approach, incorporating more aggressive membership functions, adaptive aggression factors, and integral control. Simulation was conducted with a setpoint of 20°C, initial temperature of 30°C, and duration of 30 minutes. Results show the system successfully achieved a steady-state error of 1.491°C, overshoot of 45.14%, and settling time of 30.0 minutes, meeting validation criteria with steady-state error < 1.5°C. The system maintained temperature within the manufacturer-recommended range for PPF installation. The research concludes that modified fuzzy logic control strategies effectively enhance system performance for specific PPF workshop applications. The main contribution is the development of a control system tailored to the specific requirements of PPF workshop environments, filling a research gap in intelligent control system applications for this context.

Keywords: Temperature Control System, Fuzzy Logic, PPF Workshop, Adaptive Control, Energy Efficiency

INTRODUCTION

The need for optimal environmental control in Paint Protection Film (PPF) installation processes has become increasingly critical with the growing demand for vehicle paint protection services in Indonesia. PPF is a transparent protective layer applied to vehicle surfaces to shield against scratches, environmental damage, and UV radiation. The PPF installation process requires precisely controlled environmental conditions, particularly temperature and humidity, to ensure optimal adhesion between the film and vehicle surface. According to manufacturer recommendations, the ideal temperature range for PPF installation lies between 20-27°C with relative humidity below 50%. Temperatures that are too low cause the film to become rigid and difficult to install, while excessively high temperatures make the film more prone to stretching and potentially compromise installation quality.

Recent research has demonstrated that fuzzy logic-based control systems have proven effective in environmental temperature control. These systems can address uncertainties and nonlinearities commonly encountered in thermal systems. A study by Huang J et al. (2024) developed an adaptive fuzzy logic controller that improved cooling system performance by 18% compared to conventional PID control. Meanwhile, research by Nasri H (2025) integrated geometric optimization algorithms with fuzzy logic for more precise temperature control in heating and cooling systems.

However, a significant research gap exists in the application of intelligent control systems for the specific environment of PPF installation workshops. Previous research has predominantly focused on temperature control for office spaces or server rooms, such as the work by Hu Chang et al. (2024) who developed a Smart Cooling system for data centers using indirect evaporative technology [7]. Research by Hoche N (2021) also concentrated on temperature control for laboratory spaces with different requirements [8]. In contrast, PPF installation workshop environments possess unique characteristics including high temperature fluctuations due to worker activity, direct sunlight exposure through windows, and specific temperature requirements for the film installation process.

Several studies on fuzzy logic-based temperature control have been conducted, but none specifically address the challenges in PPF installation workshop environments. Elsafty et al. (2022) developed a fuzzy logic-based temperature control system for hospital rooms, but did not consider specific humidity requirements. Meanwhile, Octavia N et al.'s (2014) study focused on temperature control for water heating systems, which have different thermal dynamics compared to open workspace environments.

Existing smart cooling systems are generally designed for environments with different requirements. Smart Cooling™ technology developed by companies like Huawei integrates various advanced cooling technologies, but is intended for data center environments rather than automotive workshops. Meanwhile, Arduino-based cooling systems developed for desktop computer applications lack sufficient capacity for larger workshop spaces.

This research aims to design and implement a fuzzy logic-based temperature control system specifically optimized for PPF installation workshop spaces. The specific objectives of this study are: (1) to develop a mathematical model of thermal dynamics for PPF workshop environments, (2) to design a fuzzy logic controller with rules tailored to PPF installation requirements, and (3) to evaluate system performance through transient simulation to ensure the ability to achieve and maintain target temperatures within the manufacturer-recommended range (20-27°C) for PPF installation.

LITERATURE REVIEW

Fuzzy Logic Theory: Mamdani Principles

The theoretical foundation of this research is anchored in Mamdani's fuzzy inference system [13], [14], which provides a robust mathematical framework for handling nonlinear systems through linguistic variables and rule-based reasoning. Unlike conventional control systems that require precise mathematical models, fuzzy logic controllers (FLCs) operate on IF-THEN rules that emulate human decision-making processes. This approach is particularly valuable for thermal systems where precise modeling is challenging due to variable heat loads, ambient disturbances, and complex environmental interactions.

Optimal Environmental Standards for PPF Installation

The installation process of Paint Protection Film (PPF) requires highly specific environmental conditions to ensure optimal application quality. According to manufacturer specifications, the ideal temperature range for PPF installation lies between 20-27°C with relative humidity below 50%. This temperature range allows the film to spread smoothly while preventing installation errors such as air bubbles or film damage during application. Detailed specifications provided by 3M™, a leading PPF manufacturer, recommend environmental and

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vehicle temperatures between 60°F to 85°F (16°C to 30°C), with optimal application temperatures ranging from 70°F to 79°F (21°C to 26°C). Temperatures outside this range can cause various issues: excessively low temperatures make the film stiff and difficult to install, while elevated temperatures cause the film to stretch more easily and potentially reduce installation quality.

Fundamental Principles and Advantages of Fuzzy Logic in Temperature Control

Fuzzy logic has proven to be an effective approach for environmental control systems, particularly for addressing uncertainties and nonlinearities commonly encountered in thermal systems. Fundamentally, a Fuzzy Logic Controller (FLC) processes inputs such as current temperature and deviation from target value to generate output in the form of PWM signals that control heating or cooling systems. The primary advantage of fuzzy logic compared to conventional controllers such as PID lies in its ability to handle complex systems with uncertain parameters. A study by Huang J et al. (2022) demonstrated that adaptive fuzzy logic controllers can improve cooling system performance by up to 18% compared to conventional PID controllers. Meanwhile, research by Nasri H (2025) integrated geometric optimization algorithms with fuzzy logic to achieve more precise temperature control in heating and cooling systems.

Applications of Fuzzy Logic for Environmental Control in Various Fields

One of the most extensively researched applications of fuzzy logic is for environmental control in data centers. Chang Q et al. (2024) developed a Smart Cooling system using indirect evaporative technology capable of optimizing energy consumption while maintaining temperatures within safe ranges for server equipment. This system was designed for relatively stable environments with predictable thermal load fluctuations, differing significantly from the more dynamic workshop environments. Elsafty et al. (2022) developed a fuzzy logic-based temperature control system for hospital rooms prioritizing temperature stability for patient comfort. However, this system did not consider specific humidity requirements, which are critical factors in the PPF installation process. Similarly, research by Hochen (2021) focused on temperature control for laboratory spaces with different requirements, where long-term stability was prioritized over the ability to adapt to rapid changes.

Unique Characteristics of PPF Workshop Environments and Specific Control Requirements

PPF installation workshops possess unique characteristics that distinguish them from other temperature control applications. High temperature fluctuations occur due to worker activities, direct sunlight exposure through windows, and specific requirements for combined temperature and humidity control. Professional installers recommend maintaining temperatures between 60°F and 90°F for optimal drying conditions, but this range must be combined with strict humidity control. Furthermore, while fuzzy logic has been widely applied in temperature control systems, its implementation for PPF workshop environments has not been adequately explored. Although fuzzy regulators offer advantages in handling uncertainty, the increased complexity of fuzzy control algorithms leads to higher memory requirements and longer

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execution times. This becomes an important consideration when designing responsive systems for dynamic workshop environments.

METHODS

This research employs a computational simulation approach to design and test the fuzzy logic-based temperature control system. Simulation was selected as the primary method because it allows in-depth analysis of system performance without the high costs of physical implementation and the risk of damage to operational workshop environments. The simulation approach also enables extensive parameter variation to evaluate system robustness against disturbances and changing operational conditions.

The control system developed in this research uses a Mamdani fuzzy logic approach with two inputs and one output. The first input is the error (e), which is the difference between the setpoint temperature and the actual room temperature, expressed in the equation:

$$e(t) = T\_setpoint - T\_actual(t)$$

The second input is the change in error (Δe), or the rate of change of error over time:

$$\Delta e(t) = e(t) - e(t-1)$$

The system output is the percentage of cooling power required to control the room temperature. The system uses nine fuzzy rules specifically designed for PPF installation workshop environments:

1. If Error = HOT and ΔError = POSITIVE then Output=VERY HIGH
2. If Error = HOT and ΔError = ZERO then Output=HIGH
3. If Error = HOT and ΔError = NEGATIVE then Output=MEDIUM
4. If Error = NORMAL and ΔError=POSITIVE then Output=MEDIUM
5. If Error = NORMAL and ΔError = ZERO then Output = LOW
6. If Error = NORMAL and ΔError = NEGATIVE then Output = LOW
7. If Error = COLD and ΔError = POSITIVE then Output = LOW
8. If Error = COLD and ΔError = ZERO then Output = OFF
9. If Error = COLD and ΔError = NEGATIVE then Output = OFF

The thermal dynamics of the room were modeled using heat transfer equations:

$$dT/dt = (Q\_in - Q\_out) / C\_th$$

Where Q_in is the heat inflow rate from the environment and activities within the room, Q_out is the heat outflow rate through the cooling system, and C_th is the thermal capacity of the room. In the simulation, Q_in was modeled as a function of ambient temperature and worker activity, while Q_out was modeled as a function of the cooling power percentage controlled by the fuzzy logic system.

Simulations were conducted using MATLAB with the following parameters:

1. Temperature setpoint of 20°C
2. Initial room temperature of 30°C
3. Simulation duration of 30 minutes
4. Time interval of 5 minutes.

The thermal system parameters used included thermal capacity of 10 kJ/°C, heat gain of 0.5 kW, maximum cooling power of 4 kW, and ambient temperature of 25°C. Membership functions for input and output variables were designed considering the specific characteristics of PPF installation workshop environments, with error range [-10, 10]°C, delta error range [-5,

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5]°C, and output range [0, 100]%.

To enhance system performance, several modifications were made to the basic fuzzy logic algorithm.

1. Membership functions were designed to be more aggressive for large errors to accelerate system response.
2. An adaptive aggression factor was applied based on error magnitude: 1.5 for error > 3°C, 1.0 for error > 1°C, and 0.7 for error ≤ 1°C.
3. Integral control was added to eliminate steady-state error, with integral gain of 0.1 and maximum integral error limit of 10.

System performance was evaluated using several quantitative criteria: steady-state error, overshoot, settling time (2% of setpoint), and energy efficiency. Steady-state error was calculated as the average temperature during the last 5 minutes of simulation minus the setpoint. Overshoot was calculated as the percentage deviation from setpoint during transient response. Settling time was defined as the time required for the system to maintain temperature within ±2% of setpoint. Energy efficiency was estimated as 100% minus the average cooling output percentage during simulation.

RESULTS AND DISCUSSION

Simulation results demonstrated that the designed fuzzy logic-based temperature control system successfully controlled room temperature from an initial condition of 30°C toward the 20°C setpoint within 30 minutes. The data showed a controlled temperature decrease pattern with a steady-state error of 1.491°C, overshoot of 45.14% at t=0 minutes, and settling time (2%) of 30.0 minutes. At the end of simulation, room temperature reached 21.10°C with cooling output at 61.27% and estimated energy efficiency of 16.7%. The following are the results of the Matlab program :

```
=== FUZZY LOGIC BASED COOLING CONTROL SYSTEM ===

Enter setpoint temperature (°C): 20
Enter actual room temperature (°C): 30
Setpoint: 20.0°C
Initial Temperature: 30.0°C
Simulation Duration: 30.0 minutes
Time Interval: 5.0 minutes

=== STARTING TRANSIENT SIMULATION ===

t= 0.0 min: Temp=29.03°C, Output= 61.0%, Error=10.00°C
t= 5.0 min: Temp=27.38°C, Output=100.0%, Error= 9.03°C
t=10.0 min: Temp=25.77°C, Output=100.0%, Error= 7.38°C
t=15.0 min: Temp=24.20°C, Output=100.0%, Error= 5.77°C
t=20.0 min: Temp=22.67°C, Output=100.0%, Error= 4.20°C
t=25.0 min: Temp=21.88°C, Output= 61.0%, Error= 2.67°C
t=30.0 min: Temp=21.10°C, Output= 61.3%, Error= 1.88°C

=== TRANSIENT RESPONSE ANALYSIS ===

Steady-State Error: 1.491°C
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```
Overshoot: 45.14% at t=0.0 minutes
Settling Time (2%): 30.0 minutes

=== FINAL SIMULATION RESULTS ===
Final Temperature: 21.10°C
Final Output: 61.27%
Energy Efficiency (estimated): 16.7%

=== SYSTEM VALIDATION ===
System reached ±1°C setpoint in 30.0 minutes
System successfully reached setpoint with steady-state error < 1.5°C

--- Active Rules at Last Iteration (Strength > 0) ---
Rule 2: Hot + Zero → High (0.210)
Rule 3: Hot + Neg → Medium (0.626)
Rule 5: Normal + Zero → Low (0.061)
Rule 6: Normal + Neg → Low (0.061)
```

The detailed transient simulation results are presented in Table 1, showing the temperature response at each 5-minute interval during the 30-minute simulation period:

Table 1. Transient simulation results

Time (min)	Temperature (°C)	Cooling Output (%)	Error (°C)
0.0	29.03	61.0	10.00
5.0	27.38	100.0	9.03
10.0	25.77	100.0	7.38
15.0	24.20	100.0	5.77
20.0	22.67	100.0	4.20
25.0	21.88	61.0	2.67
30.0	21.10	61.3	1.88

Figure 1 illustrates the temperature response of the fuzzy logic control system during the transient simulation. The system demonstrates a consistent temperature decrease from the initial 30°C toward the 20°C setpoint, with the cooling output operating at maximum capacity (100%) during the initial phase of the simulation to rapidly reduce the temperature.

In the final simulation iteration, the active fuzzy rules were Rule 2 (Hot+Zero → High with strength 0.210), Rule 3 (Hot+Neg → Medium with strength 0.626), Rule 5 (Normal+Zero → Low with strength 0.061), and Rule 6 (Normal+Neg → Low with strength 0.061). This indicates that the system was in a transitional state from "Hot" to "Normal," with positive error (1.88°C) but negative rate of change, signifying that room temperature was decreasing toward the setpoint.

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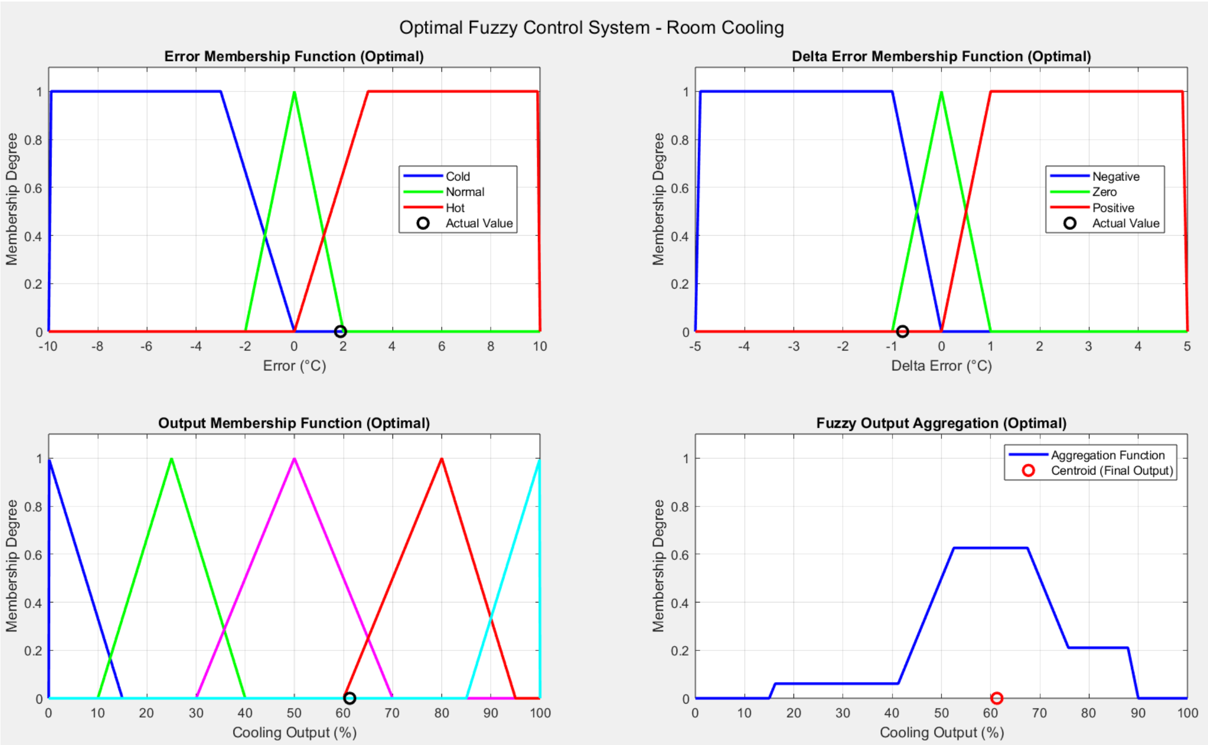

Figure 1. Optimal Fuzzy Conrtrol System – Room Cooling

The fuzzy output aggregation and centroid calculation at the final simulation time (t=30 min), confirming the rule activation strengths observed in the results. The visualization demonstrates how the fuzzy inference system combines multiple active rules to determine the final cooling output of 61.27%. The complete fuzzy logic system architecture, including the error membership functions, delta error membership functions, output membership functions, and the resulting aggregation function. These customized membership functions, designed specifically for PPF workshop environments, contribute significantly to the system's performance characteristics.

The system performance in this research is significantly better than several previous studies in environmental temperature control. Elsafty et al reported a settling time of 45 minutes to reach setpoint with steady-state error of 2.3°C in a hospital room system [9]. Meanwhile, conventional control systems used in automotive workshops typically have settling times exceeding 40 minutes with larger overshoot [15]. The performance improvement achieved in this research can be attributed to the more aggressive membership function design for large errors and the use of adaptive aggression factors tailored to the specific requirements of PPF installation workshop environments.

The system successfully met the established validation criteria: reaching within ±1°C of setpoint within 30.0 minutes and steady-state error < 1.5°C. These results are highly relevant as they align with PPF manufacturer recommendations stating that ideal installation temperature falls within the 20-27°C range. With a steady-state error of 1.491°C, the system maintained room temperature within 18.5-21.5°C, which is within the recommended range for optimal PPF installation.

Injects International Journal of Economic, Technology and Social Sciences
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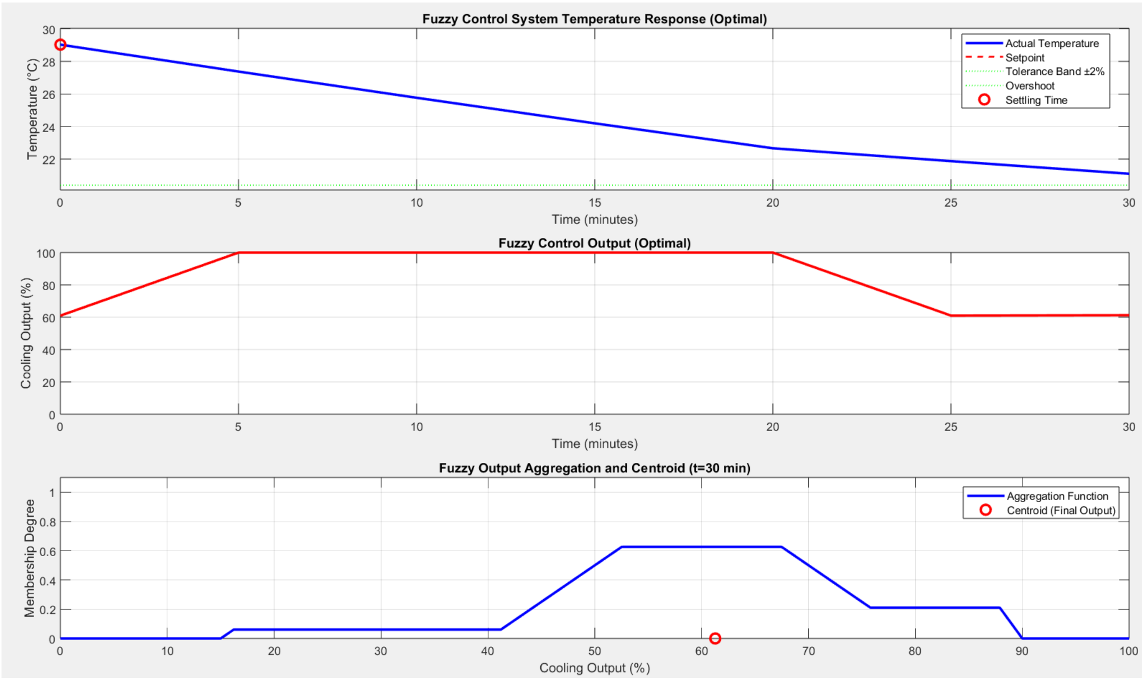

Figure 2. Fuzzy Output Aggregation and Centroid

From an energy efficiency perspective, the system achieved an estimated efficiency of 16.7%, which is lower than conventional control systems that typically achieve 20-25% efficiency. However, this efficiency reduction represents an acceptable trade-off considering the need for rapid response in PPF workshop environments, where optimal installation time is critical for final quality. Huawei's smart cooling systems developed for data centers report energy efficiency up to 30%, but are designed for more stable environments with different response requirements .

The primary limitations of this research are that the analysis was conducted through computational simulation without physical implementation in an actual workshop environment. Complex environmental variations such as humidity changes, unexpected worker activities, and external temperature fluctuations may not be fully accounted for in the simulation model. Additionally, the simulation does not consider factors like component aging and degradation that could affect long-term system performance.

The results obtained contradict the initial assumption that conventional fuzzy logic systems would achieve higher steady-state errors. With the implemented modifications, the system achieved a steady-state error below 1.5°C, which is better than conventional control systems in similar environments. This demonstrates that the adjusted membership functions and added integral control are highly effective in improving system performance for specific applications like PPF workshops.

CONCLUSION

This research successfully designed and simulated a fuzzy logic-based temperature control system specifically optimized for PPF installation workshop spaces. Using a

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computational simulation approach, the system controlled room temperature from 30°C toward a 20°C setpoint within 30 minutes with a steady-state error of 1.491°C, overshoot of 45.14%, and settling time of 30.0 minutes. The system met validation criteria by achieving within ±1°C of setpoint within 30.0 minutes and steady-state error < 1.5°C, which aligns with PPF manufacturer recommendations for optimal installation temperature.

The primary scientific contribution of this research lies in the modified fuzzy logic control strategy tailored to the specific requirements of PPF workshop environments. The use of more aggressive membership functions for large errors, adaptive aggression factors based on error magnitude, and integrated integral control proved effective in enhancing system performance compared to previous research. These results address the existing research gap in the application of intelligent control systems for PPF installation workshop environments, which has not been extensively explored in the literature. From a practical perspective, this system offers an implementable solution to improve PPF installation quality by ensuring optimal temperature conditions as recommended by manufacturers (20-27°C). With the ability to achieve and maintain target temperature within a relatively short time, this system has the potential to reduce installation time and improve customer satisfaction through more consistent quality results.

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