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Performance Optimization of Air Cooler Using Peltier and SEPIC Converter as Temperature Control

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Abstract – *Air coolers utilize an evaporative mode to achieve a lower output temperature compared to operation without this mode. The evaporative cooling process involves water that is cooled using ice cubes placed in the air cooler's water tank. The outside air entering the air cooler passes through a honeycomb structure submerged in cold water from the tank, resulting in cooler air being released. However, prolonged use of ice cubes leads to temperature increases, reducing the cooling effect of the air cooler. This research aims to develop a system that stabilizes the water temperature in the air cooler tank, ensuring consistently cooler air output. The study was conducted through simulations using MATLAB software. Based on the obtained simulation data, the water temperature can be stabilized at 25°C using the `fuzzy logic control` method. With the 5×5 fuzzy control method, the temperature reaches 25°C in 0.389 ms, whereas with the 7×7 fuzzy method, stabilization occurs at 0.407 ms. Open-loop testing results show that the temperature continuously drops to around 21°C since the test does not incorporate `fuzzy logic control`, preventing the temperature from stabilizing at 25°C.*

Keywords – *Peltier; SEPIC; Fuzzy; Air cooler; MATLAB.*

I. Introduction

INDONESIA is one of the countries with a tropical climate, making cooling a necessity for its people. Additionally, with global warming, the demand for refrigeration equipment is increasing [1]. Cooling systems serve various functions, such as reducing room temperature and preserving food, beverages, vegetables, and fruits for extended periods [2]. One of the most widely used cooling technologies is vapor compression due to its high Coefficient of Performance (COP). However, vapor compression technology utilizes refrigerant gases such as R134a, which has been banned, and R600a, which contains hydrofluorocarbon (HF) gases that can deplete the ozone layer. To address these issues, alternative technologies such as thermoelectric coolers (TEC) need to be explored.

Thermoelectric technology is based on the interaction between heat energy and electrical energy between two different metals. The thermoelectric effect is implemented in a device called the Peltier element [2]. This cooling technology has several advantages, including minimal vibration and noise, ease of maintenance, and compact size [3]. Additionally, thermoelectric technology helps reduce air pollution and ozone-depleting substances (ODS) because it does not use hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs) [4].

Peltier TECs are frequently used in cooling applications. When a DC current flows through the Peltier element, one side becomes cold as heat is absorbed, while the other side becomes hot as heat is released. This allows the component to function as either a cooler or a heater [5]. The cold side of the Peltier cools due to electron flow from a lower energy level in a p-type semiconductor to a higher energy level in an n-type semiconductor [6, 7].

Previous studies have examined the development of refrigerators with PID control that can reduce and stabilize temperatures to 22° C [3]. Another study explored the use of a thermoelectric Peltier for a medicine storage cooler box, achieving cooling temperatures of -3 to -4 °C using a radiator to dissipate heat from the hot side of the Peltier [8]. This research investigates the use of Peltier elements as water coolers in air coolers. Air coolers function based on the evaporative cooling method, requiring water as the working fluid [9]. To

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achieve a lower cooling temperature, air coolers typically use ice packs; however, ice packs eventually melt, causing the cooling effect to diminish.

To address this issue, this study proposes replacing the ice pack with a Peltier-based cooling system to maintain the water temperature in the air cooler at 25 °C. Four Peltier elements will be used in a series configuration, requiring a 48V input voltage. The voltage will be supplied by solar panels, necessitating a DC-DC converter to step down the solar panel voltage from 77.6V to 48V.

A DC-DC converter is a device that alters one DC voltage level to another [10]. Several DC-DC converter topologies exist, including SEPIC [10, 11], Buck [12, 13], Boost [14], Buck-Boost [?, 15], Zeta [?, 16], and CUK [17]. This research employs the SEPIC converter topology, which can produce output voltages lower, equal, or greater than the input voltage while maintaining the same polarity [18]. SEPIC converters exhibit smaller voltage and current ripples at the input compared to CUK, Zeta, and Buck-Boost converters [10].

Fuzzy logic control will be used to stabilize the water temperature at 25 °C. Fuzzy logic is a control approach based on the concept of partial truth, differing from crisp logic, which operates in binary (0 and 1). Fuzzy logic provides a more adaptive and responsive approach to variability and uncertainty [19]. The output of the fuzzy logic controller will be a duty cycle, which controls the output voltage of the SEPIC converter connected to the Peltier elements. By regulating the SEPIC converter's output voltage, the Peltier temperature can be controlled and stabilized according to the desired setpoint. The system block diagram is illustrated in Figure 1.

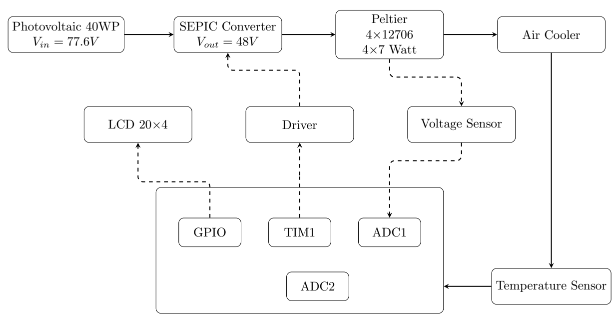


Figure 1: System Block Diagram illustrating the SEPIC converter and fuzzy logic control integration.

In Figure 1, the STM32 microcontroller is equipped with fuzzy logic control to regulate the voltage on the SEPIC converter. The temperature sensor provides feedback for error and delta error calculations, which serve as inputs for fuzzy logic control. The LCD display in the figure is used to present processed data, including voltage, temperature, and duty cycle values.

II. Research Methods

In this research, a SEPIC converter is utilized as a temperature control mechanism for the Peltier using a Fuzzy logic control method. This setup ensures that the Peltier effectively cools and maintains stable water temperature.

i. SEPIC Converter

SEPIC (Single Ended Primary Inductor Converter) is a type of DC-DC converter capable of both increasing and decreasing voltage, controlled by the duty cycle of the MOSFET switch [20]. When the duty cycle exceeds 50%, the converter functions to increase the voltage, whereas if the duty cycle is below 50%, the converter decreases the voltage. When the duty cycle is exactly 50%, the output voltage equals the input voltage. The advantage of this converter over buck-boost and other converters is that the polarity of the output voltage remains the same as the input voltage [21]. Figure 2 illustrates the SEPIC converter circuit, which consists of two inductors, two capacitors, a diode, a MOSFET, and a resistor.

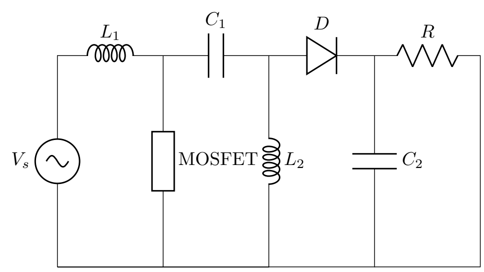


Figure 2: SEPIC Converter Circuit.

Table 1 presents the parameter design specifications of the SEPIC converter.

Table 1: Parameter Design of SEPIC Converter.

No	Parameter	Value
1	V_s (Input Voltage)	77.6V
2	V_o (Output Voltage)	48V
3	I_{in} (Input Current)	5.15A
4	I_o (Output Current)	6.66A
5	f (Switching Frequency)	40kHz
6	L_1	719 μH
7	L_2	719 μH
8	C_1	1313.6 μF
9	C_2	1313.6 μF

To determine the component values of the SEPIC converter, the following equations are used. The duty cycle is calculated using Equation (1), the inductor values are obtained using Equation (2), and the capacitor values are determined using Equation (3).

The duty cycle D is given by:

$$D = \frac{V_o}{V_o + V_s} \tag{1}$$

The inductance values L_1 and L_2 are calculated using:

$$L_1 = L_2 = \frac{V_s \times D}{\Delta i_L \times f} \tag{2}$$

The capacitance values C_1 and C_2 are given by:

$$C_1 = C_2 = \frac{V_o \times D}{R \times \Delta V_o \times f} \tag{3}$$

where: - D is the duty cycle, - V_s is the input voltage, - V_o is the output voltage, - Δi_L is the inductor current ripple, - ΔV_o is the output voltage ripple.

ii. Fuzzy Logic Control

Fuzzy logic control is a closed-loop control method applied in technical processes, including processing measured values derived from variables and set points [22]. In this study, fuzzy logic control is implemented to maintain water temperature in the water cooler and stabilize it at 25°C. The `fuzzy logic control` used consists of both 5×5 and 7×7 `Mamdani-type` rule bases, allowing for a comparative analysis between the two approaches.

The control system has two input variables: `error` (calculated as the difference between the setpoint and the actual temperature) and `delta error` (the difference between the current and previous error). Since the system is designed to stabilize the water temperature at 25°C, the setpoint is defined as 25. The fuzzy logic method is systematically designed and implemented through MATLAB-based simulations. Figure 3 illustrates the flowchart of the `Fuzzy Logic Control` stages.

`Fuzzy logic control` takes two inputs: `error` and `delta error`. The error variable ranges from -25°C to 25°C, while the delta error variable ranges from -50°C to 50°C.

After defining the membership functions, the next step is to construct the `rule base` used in this system. Table 2 presents the 5×5 `fuzzy logic rule base` for error (E) and delta error (dE).

To properly tune `fuzzy logic control`, an `open-loop simulation` is conducted to analyze the system response and determine the error values. Figure 5 presents the open-loop temperature simulation graph.

Based on the `open-loop simulation graph` (Figure 5), the `error` and `delta error` values are computed as follows:

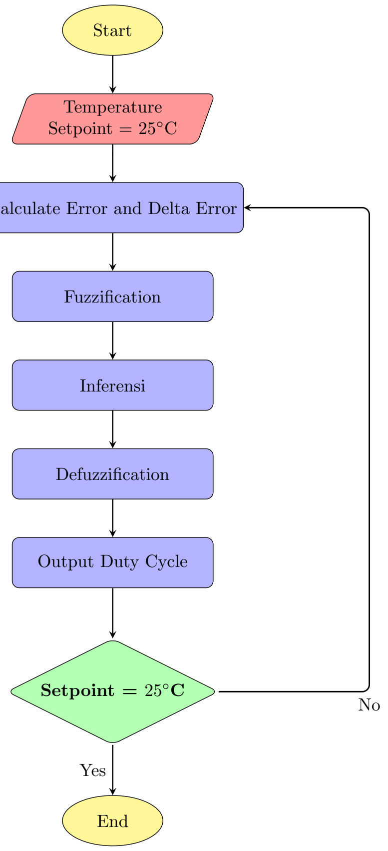


Figure 3: Flowchart of the Fuzzy Logic Control System.

Table 2: 5×5 Rule Base for Fuzzy Logic Control.

dE \ E	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

$$\text{Error} = 25 - 25.69 = -0.69 \tag{4}$$

$$\text{Delta Error} = -0.69 - (-3) = 2.31 \tag{5}$$

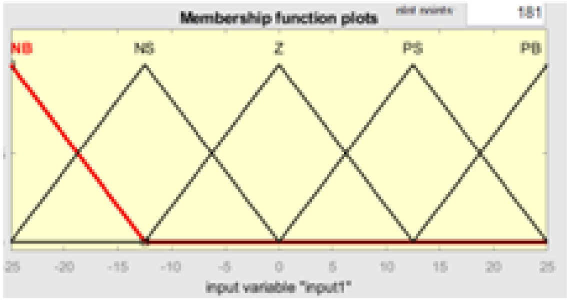
These values are used as `fuzzy logic control` inputs to optimize system performance.

iii. Fuzzification

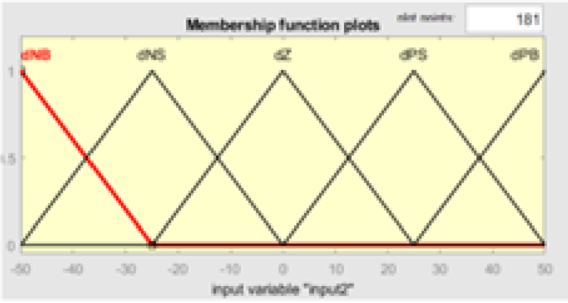
From the calculations, the obtained error value is -0.69 and the delta error value is 2.31. The membership degree values for error and delta error can be determined as follows:

The membership degree for the error:

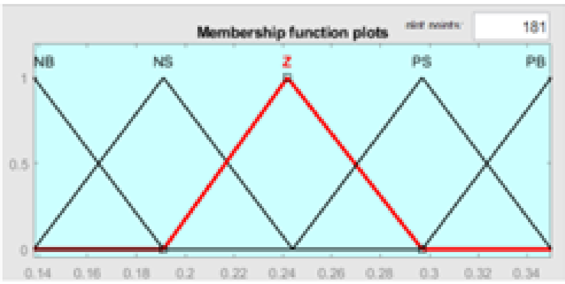
$$\mu_{NS} = \frac{0 + 0.69}{0 + 12.5} = 0.0552 \tag{6}$$



(a) Membership Function for Error.



(b) Membership Function for Delta Error.



(c) Membership Function for Output Duty Cycle.

Figure 4: Fuzzy Membership Functions.

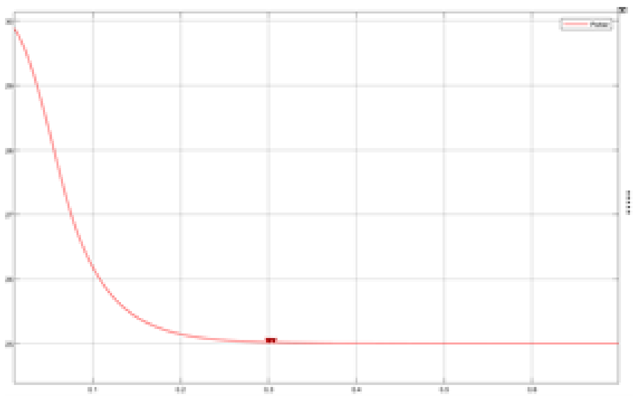


Figure 5: Open-Loop Temperature Simulation Graph.

$$\mu_Z = \frac{-0.69 + 12.5}{0 + 12.5} = 0.9448 \tag{7}$$

For the delta error:

$$\mu_{dZ} = \frac{25 - 2.31}{25 - 0} = 0.9076 \tag{8}$$

$$\mu_{dPS} = \frac{2.31 - 0}{25 - 0} = 0.0924 \tag{9}$$

iv. *Inference*

From the fuzzification results, inference is conducted based on the 5×5 rule base in Table 2.

For error (-0.69) and delta error (2.31):

1. Error values: $e_{NS} = 0.0552$, $e_Z = 0.9448$
2. Delta error values: $dZ = 0.9076$, $dPS = 0.0924$

Using Table 2, the following outputs are obtained:

1. If inputs are e_{NS} and dZ, then the output is NS:

$$E \cap dE = (0.0552, 0.9076) = 0.0552 \tag{10}$$

2. If inputs are e_{NS} and dPS, then the output is Z:

$$E \cap dE = (0.0552, 0.0924) = 0.0552 \tag{11}$$

3. If inputs are e_Z and dZ, then the output is Z:

$$E \cap dE = (0.9448, 0.9076) = 0.9076 \tag{12}$$

4. If inputs are e_Z and dPS, then the output is PS:

$$E \cap dE = (0.9448, 0.0924) = 0.0924 \tag{13}$$

v. *Defuzzification*

From the inference results, the areas of geometric shapes used for defuzzification calculations are determined.

$$A_1 = \frac{X_1 - 0.1911}{0.2419 - 0.1911} = 0.9076, \quad A_1 = 0.2372 \tag{14}$$

$$A_2 = \frac{0.2971 - X_2}{0.2971 - 0.2419} = 0.9076, \quad A_2 = 0.2470 \tag{15}$$

The areas of three geometric shapes are calculated as follows:

Building I

$$\text{Base} = 0.2372 - 0.1911 = 0.0461 \tag{16}$$

$$L_1 = \frac{(0.0461 \times 0.9076)}{2} = 0.0209 \tag{17}$$

Building II

$$L_2 = (0.2470 - 0.2372) \times 0.9076 = 0.00889448 \tag{18}$$

Building III

$$\text{Base} = 0.2971 - 0.2470 = 0.0501 \tag{19}$$

$$L_3 = \frac{(0.0501 \times 0.9076)}{2} = 0.02273 \tag{20}$$

The total area is given by:

$$\begin{aligned} A_{\text{total}} &= A_1 + A_2 + A_3 \\ &= 0.0209 + 0.00889448 + 0.02273 \\ &= 0.05252 \end{aligned} \tag{21}$$

Moment Calculations

$$M_1 = \int_{0.1911}^{0.2372} \left(\frac{(z-0.1911)}{0.2419-0.1911} \right) z\delta Z \\ = 0.004640 \tag{22}$$

$$M_2 = \int_{0.2372}^{0.2470} 0.9076 z dZ = 0.002153 \tag{23}$$

$$\begin{aligned} M_3 &= \int_{0.2470}^{0.2971} \left(\frac{(0.2791-z)}{0.2791-0.2419} \right) z\delta M_3 \\ &= \int_{0.2470}^{0.2971} \left(\frac{(0.2791-z)}{0.2791-0.2419} \right) z\delta Z \\ &= 0.005995Z \\ &= 0.005995 \end{aligned} \tag{24}$$

Total moment:

$$\begin{aligned} \text{Moment} &= M_1 + M_2 + M_3 \\ &= 0.004640 + 0.002153 + 0.005995 \\ &= 0.012788 \end{aligned} \tag{25}$$

The defuzzified output value is calculated as:

$$z^* = \frac{\text{Moment}}{A_{\text{total}}} = \frac{0.012788}{0.05252} = 0.243 \tag{26}$$

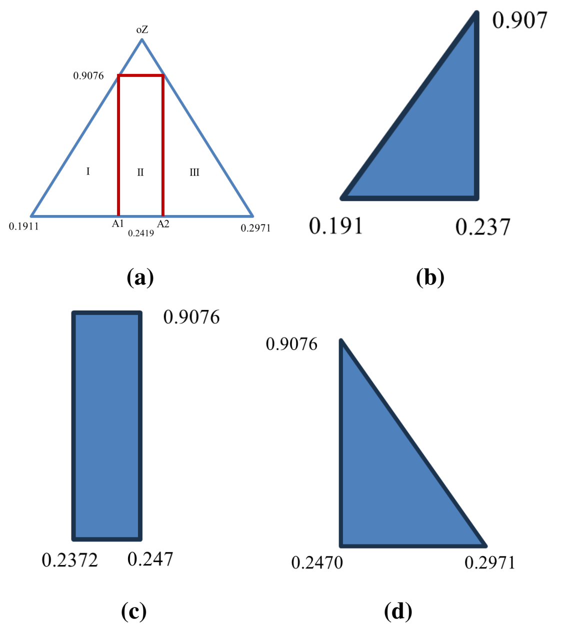


Figure 6: Geometric Representation of Defuzzification Areas. (a)Master building (b) building i, (c) building 2, (d) building 3

After several calculation steps, the `PWM output value` of the fuzzy logic control is determined as 0.243. This output is used to control the switching of `the SEPIC converter`, which provides the output voltage `for the Peltier module`. Consequently, the Peltier maintains at 25°C.

vi. Temperature Transfer Function Modeling

Temperature modeling is performed using a transfer function representation. The calculation of the temperature transfer function is conducted by first performing an open-loop experiment to determine the values of the time constant (τ) and system constant (K). The experiment was carried out by applying an input voltage of 48V to the Peltier module and recording the time required for the temperature to reach a steady state.

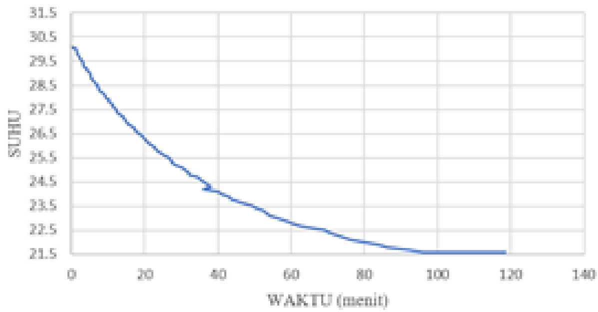


Figure 7: Temperature Open Loop Data Result Chart.

After conducting the open-loop experiment, the steady-state temperature was recorded as 21.6°C with a stabilization time of 163.01 minutes (2.71 hours). The values of the Process Value (PV) and Control Output (CO) were determined as follows:

$$\begin{aligned} PV_0 &= \text{Initial temperature} = 30.1°\text{C} \\ PV_1 &= \text{Steady-state temperature} = 21.6°\text{C} \\ CO_0 &= 0V \\ CO_1 &= 48V \end{aligned}$$

The system gain K is calculated using:

$$K = \frac{PV_1 - PV_0}{CO_1 - CO_0} = \frac{21.6-30.1}{48-0} = -0.177083 \tag{27}$$

The time constant τ is determined as:

$$\tau = \frac{T_s}{5} = \frac{2.71}{5} = 0.54 \tag{28}$$

Thus, the transfer function is given by:

$$\frac{C(s)}{U(s)} = \frac{K}{\tau s + 1} = \frac{-0.177083}{0.54s+1} \tag{29}$$

Table 3 presents the test results where the solar panel irradiation is set to 1000W/m^2.

vii. Fuzzy Logic Control with Disturbances Test

In this test, the irradiation of solar panels is varied from 1000 W/m^2 to 780 W/m^2. This aims to introduce disturbances into the system response to evaluate whether

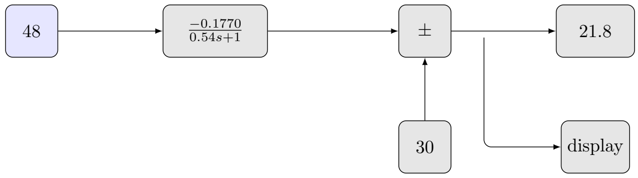


Figure 8: Open Loop Transfer Function Simulation.

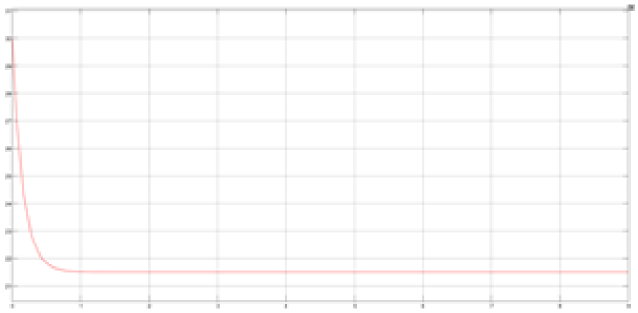


Figure 9: Open Loop Transfer Function Simulation Result.

Table 3: Temperature Simulation Test Results.

Control	Irradiance (W/m^2)	Temp. (°C)	Point (°C)	V	Err. (%)
FLC 5 × 5	1000	25	25	28.27	0
FLC 7 × 7	1000	24.99	25	28.29	0.04
Without FLC	1000	21.5	25	48.06	14

fuzzy logic control can maintain the temperature at the setpoint of 25°C. The results of this test are shown in Tables 4, 5, and 6.

Table 4: Fuzzy Logic Control 5 × 5 Testing Results

Irradiation (W/m^2)	V	Temp. (°C)	Point (°C)	Err. (%)
1000	48.06	21.5	25	14.0
980	47.92	21.52	25	13.9
960	47.78	21.55	25	13.8
940	47.59	21.57	25	13.7
920	47.43	21.6	25	13.6
900	47.24	21.64	25	13.4
880	47.05	21.67	25	13.3
860	46.83	21.71	25	13.2
840	46.62	21.75	25	13.0
820	46.36	21.8	25	12.8
800	46.07	21.85	25	12.6
780	45.74	21.91	25	12.4
Average Error				13.31%

Table 4 presents the simulation results for temperature control using the 5x5 fuzzy logic control method. Based on the obtained data, the average percentage error is 13.31%, with a stable temperature around 25°C.

Table 5 shows the data obtained from control simulations using 7 × 7 fuzzy logic control. The average percentage error is also 0.14%, similar to the 5x5 fuzzy logic control. However, when comparing Tables 4 and 5, there is a difference in the percentage error at an irradiation level of 1000 W/m^2, where the 5x5 method achieves 0% error, while the 7 × 7 method has a slight deviation of 0.04%.

Table 5: Fuzzy Logic Control 7 × 7 Testing Results

Irradiation (W/m^2)	V	Temperature (°C)	Point (°C)	Err. (%)
1000	28.29	24.99	25	0.04
980	28.26	25	25	0
960	28.22	25.01	25	0.04
940	28.17	25.01	25	0.04
920	28.14	25.02	25	0.08
900	28.10	25.03	25	0.12
880	28.06	25.03	25	0.12
860	28.02	25.04	25	0.16
840	27.97	25.05	25	0.20
820	27.92	25.06	25	0.24
800	27.86	25.07	25	0.28
780	27.83	25.08	25	0.32
Average Error				0.14%

Table 6: Testing Results Without Fuzzy Logic Control

Irradiation (W/m^2)	V	Temp. (°C)	Point (°C)	Err. (%)
1000	48.06	21.5	25	14.0
980	47.92	21.52	25	13.9
960	47.78	21.55	25	13.8
940	47.59	21.57	25	13.7
920	47.43	21.6	25	13.6
900	47.24	21.64	25	13.4
880	47.05	21.67	25	13.3
860	46.83	21.71	25	13.2
840	46.62	21.75	25	13.0
820	46.36	21.8	25	12.8
800	46.07	21.85	25	12.6
780	45.74	21.91	25	12.4
Average Error				13.31%

Table 6 presents the simulation results without fuzzy logic control, where irradiation is varied from 1000 W/m^2 to 780 W/m^2. The obtained temperature remains around 21°C, with a setpoint of 25°C, resulting in an average error percentage of 13.31%.

III. Results and Discussion

This research is conducted using simulations in MATLAB software. There are two stages of testing: closed-loop simulation testing with fuzzy 5x5 and 7 × 7, and closed-loop testing with interference. Simulations are performed using MATLAB software.

i. Closed-Loop Fuzzy Logic Control Test

This test compares the temperature results obtained using fuzzy logic control with 5x5 and 7 × 7 rule sets. Figure 10 illustrates the circuit of the system used to reduce the temperature of the Peltier. The system consists of two 200WP solar panels connected in series, serving as the input voltage supply to the SEPIC converter. The SEPIC converter controls the input voltage to the Peltier, ensuring that the generated temperature can be regulated and maintained at the desired set point of 25°C.

Fuzzy logic control receives input from temperature readings and produces an output in the form of a duty cycle value. This duty cycle regulates the MOSFET switching in the SEPIC converter, thereby controlling the converter's output voltage. The Peltier's temperature control is based on the transfer function derived in the previous discussion.

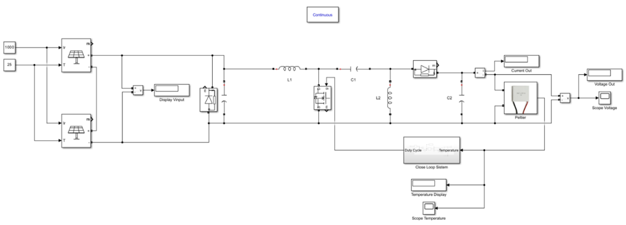


Figure 10: System Circuit for Peltier Temperature Reduction.

Table 3 shows that the smallest percentage error is achieved when using fuzzy logic control 5x5, where the resulting temperature closely matches the desired set point of 25°C. In contrast, the simulation without fuzzy logic control results in a temperature of 21.5°C. This occurs because the input voltage to the Peltier is unregulated, preventing the temperature from stabilizing at the set point.

There is a difference in the time required to reach the steady-state temperature between Figures 11a and 11b. In Figure 11a, the time to reach steady-state is 0.389ms, while in Figure 11b, the steady-state value is obtained at 0.407ms.

IV. Conclusion

Based on the simulations that have been conducted, the following conclusions can be drawn:

1. To stabilize the temperature, a control system is required to maintain the temperature at the desired setpoint. One of the effective control methods is `fuzzy logic control`. From the comparison between a system without control and a system using fuzzy logic control, it was observed that without control, the temperature could not stabilize at 25°C and continued to drop to 21°C.
2. From the comparison between the 5×5 and 7×7 fuzzy logic control methods, it was found that the temperature stabilization time to reach 25°C with the 5x5 fuzzy logic control was faster, taking 0.389 ms, compared to the 7×7 fuzzy logic control, which took 0.407 ms. However, when evaluated based on the average percentage error relative to the setpoint, both methods achieved the same error rate of 0.14%.

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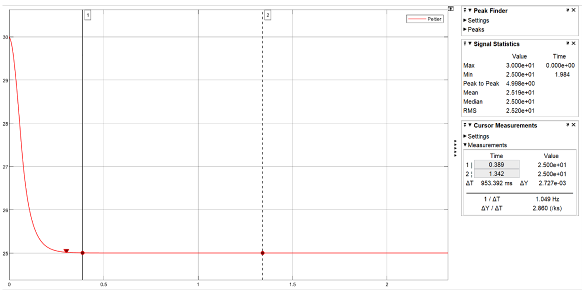
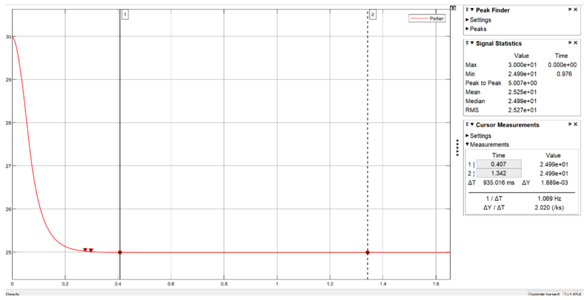
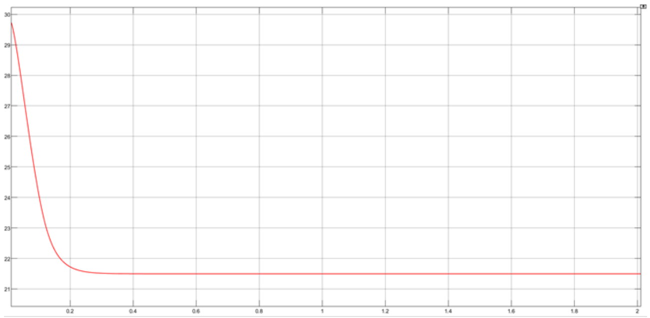


(a) Temperature response with Fuzzy 5×5.



(b) Temperature response with Fuzzy 7×7.



(c) Temperature response without fuzzy logic control.

Figure 11: System Simulation Graph Using MATLAB: (a) Fuzzy 5×5, (b) Fuzzy 7×7, (c) Without fuzzy logic control.

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