Wireless Temperature Monitoring and Control of a Peltier-Based Thermoelectric Cooler Using ESP32 and PWM Controller

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***Abstract*—This paper presents the design, development, and performance evaluation of a wireless temperature monitoring and control system for a thermoelectric cooler based on the Peltier effect. Utilizing the ESP32 microcontroller for wireless communication and PWM signal generation, the system efficiently drives a TEC1-12706 module and associated cooling fan. A DS18B20 digital temperature sensor enables accurate temperature readings, which are transmitted in real-time to a custom-built web interface hosted by the ESP32. The cooling mechanism is activated once the sensed temperature surpasses a user-defined threshold, with PWM duty cycles dynamically adjusted for precise thermal regulation.**

The system architecture emphasizes energy efficiency, real-time responsiveness, and scalability, making it suitable for smart refrigeration, embedded electronics cooling, and environmental sensing applications. The hardware implementation was prototyped and validated under varying thermal conditions, confirming the effective drop in temperature within 30 seconds of activation. The inclusion of a feedback control algorithm ensures adaptive and autonomous operation, while the minimalistic web interface facilitates remote monitoring. This IoT-enabled thermal management system highlights the potential of embedded microcontrollers for compact, wireless, and intelligent cooling solutions.

***Index Terms*—ESP32, Peltier module, Thermoelectric cooler, PWM controller, IoT, Wireless monitoring, Embedded system**

I. Introduction

Temperature regulation is a critical factor in various industrial, medical, and consumer applications. Whether it is to maintain the stability of electronic components, preserve sensitive biological samples, or ensure user comfort in smart home environments, the ability to control and monitor temperature precisely and efficiently is of utmost importance.

Thermoelectric cooling, particularly using Peltier modules, has gained popularity due to its compact size, lack of moving parts, low maintenance, and ability to provide both heating and cooling effects. However, most traditional thermoelectric systems operate as closed units without real-time feedback or remote access capabilities. This limits their flexibility and effectiveness in dynamic environments where temperature changes frequently.

With the advancement of the Internet of Things (IoT), integrating smart microcontrollers such as the ESP32 with wireless communication capabilities has opened the door to real-time monitoring and adaptive control systems. The ESP32, a low-cost, low-power microcontroller with built-in Wi-Fi and Bluetooth, enables seamless connectivity and control through web-based interfaces or mobile applications.

This project presents a comprehensive system that combines a thermoelectric Peltier-based cooler with a wireless temperature monitoring and control unit. By leveraging the ESP32, a DS18B20 digital temperature sensor, and a PWM (Pulse Width Modulation) controlled fan and Peltier module, the system can automatically regulate temperature and display live data on a custom-designed webpage.

The proposed system is particularly suited for applications in portable refrigeration, electronics cooling, and remote environmental sensing. Additionally, the use of PWM allows efficient power management, while wireless feedback provides users with real-time visibility and control over the system's performance.

II. Literature Review

Several studies have explored thermoelectric cooling systems using Peltier modules as an eco-friendly alternative to traditional compressor-based refrigeration. This model [1] utilized TEC1-12706 Peltier modules along with microcontrollers, temperature sensors, and relays to maintain user-defined temperatures. The working principle involves applying a DC voltage to the Peltier module, which creates a temperature difference across its two surfaces—one side absorbs heat (cooling side) while the other releases heat (heating side). Heat from the hot side is effectively dissipated using aluminum heat sinks and fans, ensuring optimal thermal management.

The main advantages of thermoelectric cooling include compact size, portability, absence of moving parts, low noise, and the elimination of harmful refrigerants like CFCs. These systems are ideal for applications such as portable refrigerators, vaccine carriers, and cooling solutions in remote or sensitive environments. However, drawbacks include lower energy efficiency compared to conventional compressor-based systems and reduced cooling performance in high ambient temperatures. Despite this, thermoelectric systems offer practical benefits in specialized scenarios.

These findings support the use of PWM control and embedded systems like ESP32 for precise temperature regulation, enabling real-time control and monitoring of thermoelectric cooling units.

Thermoelectric cooling systems using Peltier modules have been investigated as reliable solutions for cooling both solid and liquid media. In this study [2], a two-circuit system was developed where Peltier cells were used to cool a liquid through an aluminum heat exchanger. The system included a primary cooling loop powered by Peltier modules and a secondary loop for isolated fluid transfer. The modules work based on the Peltier effect, where electric current causes one side of the module to absorb heat and the other to release it, allowing targeted cooling.

The advantages of such systems include compactness, absence of moving parts, silent operation, and suitability in applications where hygiene, vibration-free operation, or clean-room compatibility is essential. However, one major drawback is their relatively low efficiency, with coefficient of performance (COP) significantly lower than that of conventional compressor-based systems. Additionally, thermal management of the hot side is critical to maintain stable performance.

These insights demonstrate the effectiveness of thermoelectric modules in specific applications and support the use of PWM control and embedded platforms like ESP32 to enhance precision, energy efficiency, and remote monitoring capability.

This study [3] for applications ranging from microelectronics to wearable systems. The operation relies on applying current through P-N junction pairs, which transfers heat from one side of the device to the other. This principle is particularly useful for compact, vibration-free, and localized cooling. Advances in materials such as Bi_2Te_3-based superlattices and nanostructured alloys have significantly improved the thermoelectric figure of merit (ZT), enhancing cooling performance at room temperatures. The main advantages of these systems include silent operation, compactness, fast response, and environmental safety due to the absence of refrigerants. However, drawbacks such as low energy efficiency, sensitivity to thermal resistance, and limitations in high heat-load conditions still challenge widespread adoption. These insights support the integration of PWM control and embedded systems like the ESP32 for smart thermal management, enabling efficient, programmable, and real-time control of Peltier-based cooling systems.

This study [4] focused on improving cooling efficiency through multi-stage Peltier module configurations. A two-stage thermoelectric cooler (TEC) design utilizing separate pulse currents was developed to enhance transient supercooling effects. The system operates by applying pulse currents independently to the cold and hot stages, allowing for optimized temperature drops and longer supercooling holding times. This method takes advantage of the Peltier effect at the cold end and minimizes Joule heating by carefully timing the pulses. The main advantages of this approach include a significant increase in temperature drop compared to single-stage TECs, flexible control, and suitability for applications requiring rapid thermal cycling. However, drawbacks include increased system complexity, energy losses due to Joule heating at high currents, and the need for precise timing control. These findings demonstrate the value of pulse-based cooling strategies and support the use of PWM control and embedded platforms like ESP32 for dynamic and energy-efficient temperature regulation in Peltier-based systems.

This study [5] as alternatives to vapor compression-based refrigeration for localized and compact cooling applications. In one experimental study, a foam-based mini cooler was constructed using a TEC1-12706 Peltier module sandwiched between internal and external heat sinks, aided by cooling fans. When powered by a 12V DC source, the Peltier module absorbed heat from the cooler's interior and transferred it to the external environment via the heat sinks, demonstrating the Peltier effect in practice.

The setup successfully lowered internal temperatures from ambient to 18.5°C within minutes and achieved a coefficient of performance (COP) of over 0.5. Advantages of this approach include portability, absence of refrigerants, silent operation, and the ability to precisely regulate temperatures. However, thermal losses due to heat sink inefficiencies and lower COP compared to conventional systems are noted limitations. These findings highlight the practical use of Peltier-based systems and support the integration of PWM-controlled embedded platforms like ESP32 for improved thermal efficiency, automation, and real-time monitoring.

This study [6] for their potential in low-power, compact ventilation solutions. In one study, a cooler utilizing six TEC1-12706 modules was tested under varying thermal and flow conditions to analyze performance and cost characteristics. The system operates by transferring heat through the thermoelectric modules using DC input power, with heat sinks and fans used for thermal dissipation. Exergoeconomic modeling was applied to evaluate the cost-effectiveness and performance under real-world operating ranges.

The study showed that cooling cost is influenced by parameters such as air inlet temperature, water flow rate, and input power. An optimal point was observed where excessive input power reduced exergetic efficiency and raised cost, while moderate input power improved performance. Advantages of the system include silent operation, modular design, and reduced refrigerant dependency, while drawbacks include low energy efficiency and performance limitations under high power loads. These findings support the use of PWM-based control and ESP32 microcontrollers to dynamically adjust power input, improve energy usage, and enable wireless temperature regulation in thermoelectric cooling systems.

[7] explored as alternatives to vapor compression refrigeration, especially for applications requiring compact size, silent operation, and eco-friendly cooling. In one study, the performance of single-stage and binary (double-stage) Peltier configurations—both discrete and consecutive—was analyzed through experimental and CFD methods. These systems work

on the Peltier effect, where a voltage applied across the thermoelectric module causes heat transfer from one side to the other. For the air-to-water cooling model, discrete binary configurations demonstrated higher cooling rates, while the single Peltier model achieved better energy efficiency (higher COP).

The study highlighted several advantages such as fast response, low noise, no moving parts, and the absence of refrigerants. However, challenges included higher power consumption in multi-stage setups and a notable decline in COP over time. The research also emphasized the importance of Peltier arrangement and proper heat exchanger design to enhance cooling performance. These findings align with and support the use of PWM control techniques and embedded platforms like the ESP32 to regulate power input efficiently and achieve precise, real-time temperature control in thermoelectric systems.

This study [8]Research into temperature control using thermoelectric modules has highlighted the effectiveness of PWM-based methods in regulating heat transfer through Peltier elements. One study demonstrated how a Peltier module could be used to control the temperature of a small aluminum plate by applying variable current generated through a PWM signal. The system included a feedback loop using temperature sensors and current-sensing circuits, controlled by a PIC microcontroller. Cooling fans were activated only during the cooling phase to optimize performance. The system successfully regulated temperature between 35°C to 70°C with repeatable thermal cycles.

Advantages of the approach included accurate control, simple construction, and minimal mechanical components, making it suitable for compact cooling systems. However, challenges such as slower cooling cycles and the need for precise calibration of current and fan operation were noted. These findings emphasize the potential of PWM-controlled thermoelectric systems and support the integration of ESP32 microcontrollers for real-time feedback, improved automation, and web-based temperature monitoring in advanced cooling applications.

[9] explored for compact and eco-friendly refrigeration solutions. One study investigated a TEC-based refrigerator controlled using an Arduino platform and a PID feedback loop to maintain target temperatures with high precision. The system used the TEC1-12706 module, water-cooled heat sinks, and DHT22 sensors for accurate real-time temperature control. The PID algorithm was implemented to modulate input current, allowing precise adjustment of the cooling rate while ensuring minimal overshoot and fast stabilization.

The system achieved a maximum temperature span of 51°C and a coefficient of performance (COP) ranging from 0.73 to 0.1. The advantages included rapid cooling, precise control, silent operation, and good performance in constrained environments. However, drawbacks such as reduced COP over time, sensitivity to thermal losses, and complexity of water cooling circuits were also noted. These findings support the integration of PWM control and embedded systems like ESP32 for real-time regulation, enhanced energy efficiency, and wireless temperature monitoring in advanced thermoelectric applications.

The study [10] have been effectively employed in precision applications such as solid-state laser cooling, where temperature stability is essential for optimal performance. One method utilized Peltier modules in conjunction with an Arduino Nano and thermistors to control the temperature of a Ti:Sapphire laser crystal using a proportional-integral (PI) control approach. The control signal was applied through PWM and amplified using an op-amp and power transistor, enabling accurate thermal regulation within a narrow range.

The implementation featured a simulation-driven design process and experimental validation using MATLAB and Simulink. Advantages included precise and efficient temperature control, open-source hardware compatibility, and reproducibility of the method. However, the system's complexity increased due to the need for analog interfacing, power regulation, and tuning of the control parameters. These findings reinforce the importance of PWM-driven control systems and support the use of embedded microcontrollers like the ESP32 for compact, cost-effective, and real-time thermal management in Peltier-based cooling applications.

An automatic cooling system using a Peltier element, based on fuzzy logic, was designed to improve the thermal management of computer processors. The system reads temperature values from the processor cores and sends them via serial communication to a microcontroller. Fuzzy logic is implemented on the microcontroller to determine the appropriate PWM values for controlling the Peltier element and fan. The cooling system circulates liquid through a waterblock attached to the Peltier's cold side, enhancing cooling efficiency [11].

The integration of fuzzy logic allows for dynamic temperature control with high precision. Compared to traditional air and water cooling systems, this system significantly lowers the average core and package temperatures during both idle and benchmark testing. Additionally, it ensures more stable processor performance and longevity due to better thermal regulation [11].

The system relies on multiple hardware components such as a microcontroller, MOSFET, and a dedicated software interface, making it more complex and potentially less reliable if any part fails. The use of Peltier elements, while effective, can lead to higher power consumption and heat generation on the hot side of the element, which needs to be managed properly [11].

The concept demonstrated in the reviewed system aligns closely with this project's goal of using PWM to control cooling hardware via the ESP32 microcontroller. While the original system uses ATmega328, similar control logic and PWM signal generation can be replicated and enhanced using ESP32's multi-channel PWM capabilities and greater processing power. This makes the integration of fuzzy logic with real-time cooling via PWM signals both feasible and scalable for ESP32-based systems [11].

The study proposes an optimization-based design of a Peltier air cooler using the Taguchi method. The system employs thermoelectric modules to generate cooling, with variations in three main parameters: number of modules, air flow rate, and input power. By utilizing a controlled experimental setup and orthogonal array (L16), the study evaluates the influence of each factor on the cooler's coefficient of performance (COP), exergetic efficiency, and cost per unit of cooling. Measurements are carried out through a test rig with digital flow meters and thermocouples, and optimization is based on signal-to-noise (S/N) ratio calculations [12].

The study demonstrates that increasing the number of Peltier modules improves COP and exergetic efficiency significantly, especially when the total input power is distributed across multiple modules. The use of the Taguchi method allows for efficient optimization using a minimal number of experiments. Additionally, economic evaluation through specific exergy costing provides a comprehensive understanding of the trade-offs between performance and cost [12].

While more modules enhance performance, they also increase the capital and operational costs. There's a saturation point beyond which adding modules yields diminishing returns due to increased internal resistance. Similarly, excessive air flow or input power can negatively affect efficiency. The study also indicates that the effect of air flow on COP is relatively minor, suggesting limited flexibility in this parameter [12].

This research provides valuable insights for PWM-based thermal management systems using ESP32. Since PWM is essential for controlling input power and fan speed, integrating similar optimization logic on ESP32 can enhance energy efficiency and performance. Furthermore, understanding the nonlinear relationship between power input and cooling output will support more adaptive PWM control strategies. This makes the study highly relevant to embedded applications where efficient thermal management is crucial [12].

This study investigates the feasibility of using Peltier cells as thermoelectric generators to power telemetry and environmental monitoring systems. The experiments focused on how temperature gradients between the hot and cold sides of the cell affect voltage generation. Several types of Peltier cells were tested under laboratory and simulated real-world conditions to assess their energy output, stability, and operational reliability. Voltage outputs increased logarithmically or exponentially with greater temperature differentials, reaching up to 3.5 V under optimal lab conditions [13].

Peltier cells provide a silent, compact, and mechanically simple method for energy harvesting. In scenarios where solar energy is not feasible due to vandalism or environmental factors, thermoelectric generators offer a viable alternative for continuous, autonomous power supply. The study concluded that under certain conditions (like 50–129°C gradients), Peltier-based systems can generate enough voltage to charge 12 V batteries or power low-consumption wireless sensors [13].

Although Peltier cells can generate usable voltage, their current output is relatively low, making it difficult to power devices with higher energy demands. Efficiency drops significantly if the temperature differential is too small or if the hot/cold sides are not properly managed. Series and parallel connections also pose balancing issues due to uneven heat distribution, resulting in voltage drops and inefficient performance [13].

The research provides critical insights into using thermoelectric generation for low-power embedded systems like those based on the ESP32. With PWM control, ESP32 can modulate energy storage or sensor activation cycles based on the availability of harvested energy. Though not highly efficient, this method aligns well with remote applications needing intermittent power, especially when solar options are unavailable or impractical [13].

III. Methodology

The proposed system integrates a thermoelectric cooling mechanism with an IoT-based temperature monitoring and control system. The overall architecture is designed to regulate temperature using a Peltier module, with real-time data acquisition and wireless communication facilitated by the ESP32 microcontroller.

A. System Components

The key components used in the implementation are:

- **ESP32 Microcontroller:** Serves as the core controller. It reads temperature data from the sensor and controls the Peltier module using PWM signals. It also hosts a web interface for live monitoring via Wi-Fi.
- **DS18B20 Temperature Sensor:** A waterproof digital sensor used to provide accurate and real-time temperature readings from the heat sink.
- **Peltier Module (TEC1-12706):** Converts electrical energy into a temperature gradient based on the Peltier effect. The cold side cools the target area, while the hot side is dissipated using a heat sink and fan.
- **PWM Fan:** Used to actively cool the hot side of the Peltier to maintain efficiency and prevent thermal saturation.
- **MOSFET :** Controls power delivery to the Peltier based on PWM signals from ESP32.

B. Peltier Effect and Thermoelectric Cooling Principle

The Peltier effect is a thermoelectric phenomenon where heat is absorbed or released at the junction of two dissimilar conductors when an electric current passes through it. When applied in a Peltier module, one side becomes cold while the opposite side becomes hot. This direct solid-state mechanism offers compact, vibration-free, and noise-free cooling, ideal for precision electronics and embedded applications. The direction of heat flow can be reversed by inverting the polarity of the current, making Peltier modules suitable for both heating and cooling scenarios.

Unlike traditional compressor-based systems, thermoelectric modules offer better control at smaller scales and are easily driven using low-voltage DC power. However, they are inherently inefficient and require proper heat dissipation systems to operate within safe limits.

C. System Design

The ESP32 continuously monitors temperature from the DS18B20 sensor. Based on a user-defined threshold (e.g., 35C), the ESP32 triggers the PWM controller to activate the Peltier module. PWM (Pulse Width Modulation) helps in adjusting the intensity of cooling by controlling the duty cycle of the power delivered to the Peltier.

The control logic follows a basic feedback loop:

1) Measure the current temperature using DS18B20.
2) If temperature $>$ threshold, turn on PWM to drive Peltier.
3) Else, keep the Peltier turned off.
4) Continuously update the temperature on the web dashboard.

D. Web Interface

A lightweight HTML and JavaScript-based webpage is served from the ESP32 over Wi-Fi. This page displays live temperature readings and the status of the cooler. The ESP32 acts as a local server, handling GET requests and responding with updated sensor values in real-time (every 2 seconds).

E. Power Management and Safety

The system operates at 12V to drive the Peltier and fan. A step-down voltage regulator supplies 3.3V to the ESP32. Heat dissipation is managed using a heat sink attached to the Peltier's hot side and an always-on fan. Safety measures include:

- Heat sink with thermal paste to improve efficiency
- Fan running continuously to avoid thermal buildup
- Software logic to shut off Peltier if sensor is disconnected or fails

F. PWM Control Logic

The PWM signal is generated using the ESP32's built-in timer channels. The PWM frequency and duty cycle are adjusted based on how far the sensed temperature exceeds the threshold, allowing for more precise temperature regulation and energy efficiency.

$$\text{Duty Cycle} = \frac{T_{\text{measured}} - T_{\text{threshold}}}{T_{\text{max}} - T_{\text{threshold}}} \times 100\%$$

Where:

- T_{measured} = current temperature
- $T_{\text{threshold}}$ = temperature set point (e.g., 50°C)
- T_{max} = maximum expected temperature (e.g., 70°C)

The use of PWM is crucial for controlling not just the ON/OFF state, but also the intensity of the cooling effect. This minimizes energy consumption and reduces wear on the Peltier module. As the temperature rises, the duty cycle increases, ensuring proportional power delivery.

G. Implementation Summary

The entire circuit was prototyped on a breadboard and later soldered on a PCB for stability. The firmware was written using the Arduino IDE and tested in real-time. The system was calibrated using multiple temperature thresholds and evaluated for cooling efficiency, responsiveness, and web interface stability.

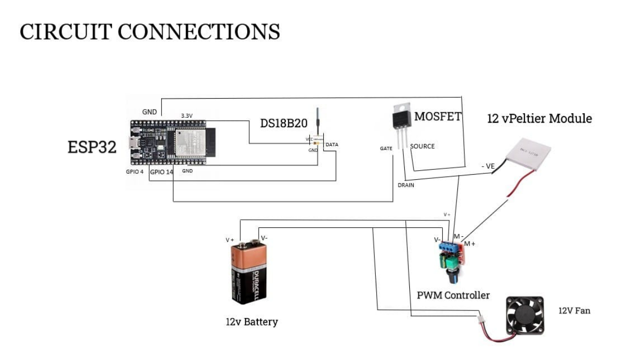

Fig. 1: Circuit Diagram of the Proposed System

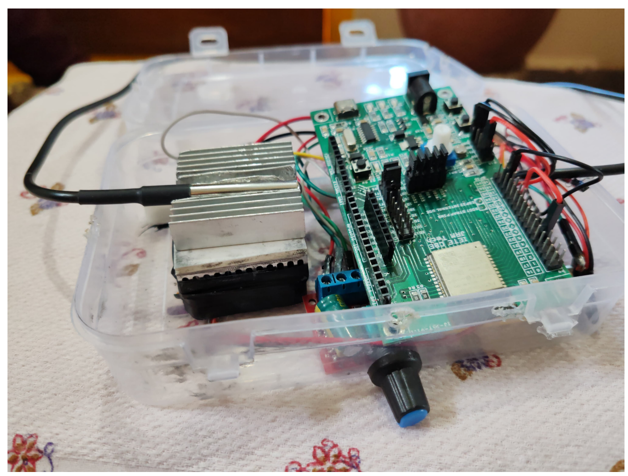

Fig. 2: Prototype image

The implemented prototype of the Peltier-based thermoelectric cooling system was tested under various temperature conditions to evaluate its efficiency and responsiveness. The system was designed to activate the Peltier module when the sensed temperature exceeded 35°C. The temperature was monitored in real time using the DS18B20 digital sensor interfaced with the ESP32 microcontroller.

H. Temperature Monitoring Results

The system successfully recorded temperature data at regular intervals and displayed it on the web interface using the Wi-Fi capabilities of the ESP32. Table I shows a sample of the real-time readings obtained during testing.

TABLE I: Sample Temperature Readings

Time (s)	Temperature (°C)
0	35.06
10	31.2
20	27.7
30	25.4

I. Cooling Performance Analysis

As seen in the graph in Fig. 3, once the temperature exceeded the 35°C threshold, the PWM-controlled Peltier module was activated. Within 30 seconds, the temperature dropped by approximately 10°C, demonstrating effective thermal regulation.

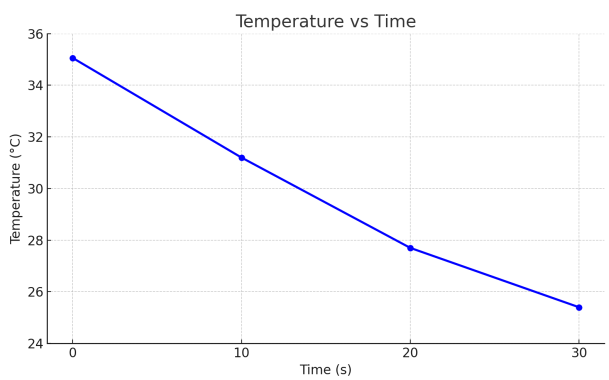

Fig. 3: Temperature VS Time Graph

J. Web Interface Screenshot

Fig. 4 displays the custom HTML-based interface used to monitor live temperature data. The webpage is hosted on the ESP32 module and refreshes every 2 seconds, allowing users to visualize current thermal conditions remotely.

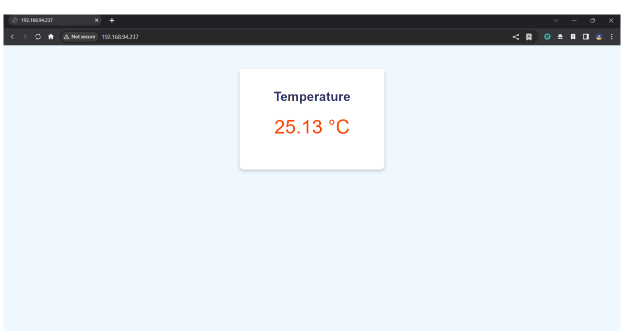

Fig. 4: Web interface showing real-time temperature monitoring

K. Power Consumption

During active cooling, the system drew approximately 4–6A at 12V for the Peltier module, resulting in a power consumption of around 48–72W. The ESP32 and DS18B20 sensor operated at 3.3V with minimal current draw, making the control system highly efficient. The high current drawn by the Peltier module required the use of a dedicated 12V power source and a proper heat sink to manage thermal load effectively.

IV. Conclusion

This project successfully demonstrates the design and implementation of a Peltier-based thermoelectric cooling system controlled by a PWM signal from an ESP32 microcontroller. The system activates the cooling process when the temperature exceeds a predefined threshold, utilizing a DS18B20 temperature sensor for real-time monitoring.

The integration of a web-based IoT interface allowed users to remotely observe temperature changes, making the system suitable for smart embedded applications. The results confirmed effective thermal regulation and quick response time, with a noticeable drop in temperature after activation of the Peltier module.

The hardware was compact, energy-efficient, and capable of running autonomously with minimal user intervention. This project lays the groundwork for further expansion into closed-loop control systems or smart HVAC prototypes using similar components.

References

[1] M. Kalimuthu., R. Subashini., U. Mohammed Al Rasheeth., and M. Sabaeshwaran., "Peltier based temperature controlled smart mini refrigerator," in *2021 International Conference on Advancements in Electrical, Electronics, Communication, Computing and Automation (ICAECA)*, 2021, pp. 1–5.

[2] R. Guráš and M. Mahdal, "Use of peltier modules for liquid cooling," in *2021 22nd International Carpathian Control Conference (ICCC)*, 2021, pp. 1–4.

[3] L. A. Nimmagadda, R. Mahmud, and S. Sinha, "Materials and devices for on-chip and off-chip peltier cooling: A review," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 11, no. 8, pp. 1267–1281, 2021.

[4] Y.-W. Gao, H. Lv, X.-D. Wang, and W.-M. Yan, "Enhanced peltier cooling of two-stage thermoelectric cooler via pulse currents," *International Journal of Heat and Mass Transfer*, vol. 114, pp. 656–663, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0017931017319142

[5] M. Fairuz Remeli, N. Ezzah Bakaruddin, S. Shawal, H. Husin, M. Fauzi Othman, and B. Singh, "Experimental study of a mini cooler by using peltier thermoelectric cell," *IOP Conference Series: Materials Science and Engineering*, vol. 788, no. 1, p. 012076, apr 2020. [Online]. Available: https://dx.doi.org/10.1088/1757-899X/788/1/012076

[6] H. Moria, S. Pourhedayat, H. S. Dizaji, A. M. Abusorrah, N. H. Abu-Hamdeh, and M. Wae-hayee, "Exergoeconomic analysis of a peltier effect air cooler using experimental data," *Applied Thermal Engineering*, vol. 186, p. 116513, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1359431120339879

[7] F. Afshari, M. A. Ceviz, E. Manay, M. Ceylan, and B. Muratçobanoğlu, "Performance analysis of air-to-water binary thermoelectric peltier cooling systems and determination of optimum arrangement," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 44, no. 9, p. 424, 2022. [Online]. Available: https://doi.org/10.1007/s40430-022-03737-y

[8] D.-Y. Pang, W.-S. Jeon, K.-H. Choi, T.-K. Kwon, N.-G. Kim, and S.-C. Lee, "Temperature control using peltier element by pwm method," in *Proceedings of the International Conference on Control, Automation and Systems (ICCAS 2005)*. KINTEX, Gyeonggi-Do, Korea: ICCAS, June 2–5 2005, pp. 1400–1404.

[9] A. Kherkhar, Y. Chiba, A. Tlemçani, and H. Mamur, "Thermal investigation of a thermoelectric cooler based on arduino and pid control approach," *Case Studies in Thermal Engineering*, vol. 36, p. 102249, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214157X22004956

[10] F. F. Montalvão, I. C. de Almeida, V. P. Pinto, B. P. de Oliveira, F. M. M. Yasuoka, and J. C. de Castro Neto, "Peltier-based temperature regulation: A method for performance optimization in solid-state lasers," *MethodsX*, vol. 13, p. 102873, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S221501612400325X

[11] R. K. R, A. H. Hasugian, and R. P. Putra, "Application of fuzzy logic in automatic cooling computer design using peltier based on atmega328 microcontroller," *JURNAL INFOKUM*, vol. 10, no. 1, pp. 278–287, 2021. [Online]. Available: http://infor.seaninstitute.org/index.php/infokum/article/view/746

[12] Z. R. Abdulghani, "A novel experimental case study on optimization of peltier air cooler using taguchi method," *Results in Engineering*, vol. 16, p. 100627, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2590123022002973

[13] R. Hájovský, M. Pieš, and L. Richtár, "Analysis of the appropriateness of the use of peltier cells as energy sources," *Sensors*, vol. 16, no. 6, p. 760, 2016. [Online]. Available: https://www.mdpi.com/1424-8220/16/6/760