An IoT-Driven Thermoelectric HVAC System for Compact and Sustainable Cooling

Mrs. C D Rananaware[1], Ruchita Magar[2], Sravani Pande[3], Gayatri Raykar[4]
[1]*Assistant Professor, ENTC AISSMS COE, Pune*
[2,3,4]*Student, ENTC AISSMS COE, Pune*

***Abstract*—This paper presents the design and implementation of a smart HVAC (Heating, Ventilation, and Air Conditioning) system using thermoelectric cooling based on the Peltier effect integrated with an Internet of Things (IoT) framework. Unlike conventional vapour-compression refrigeration systems, the proposed system uses semiconductor-based cooling modules (TEC1- 12706) controlled by a microcontroller (STM32F103) to achieve localized cooling. The system incorporates temperature sensing, intelligent control, and remote monitoring through Wi-Fi communication. The objective is to develop a compact, energy-efficient, and environmentally friendly cooling system suitable for small-scale applications.**

***Index Terms*—Thermoelectric Cooling, Peltier Module, HVAC, IoT, STM32, Smart Cooling, Embedded Systems**

I. INTRODUCTION

Conventional HVAC systems rely heavily on vapor-compression refrigeration cycles, which involve the use of refrigerants such as hydrofluorocarbons (HFCs). These refrigerants contribute significantly to global warming and environmental degradation. The study of IoT (Internet of Things) focuses on the knowledge of sensors, actuators, and other objects which are connected to Internet, as connecting the people with the virtual world. IoT will also encourage the number of application latest applications such as environmental monitoring, healthcare, and efficient management of energy in smart homes.

Heating, Ventilation and Air Conditioning (HVAC) are the most energy required appliances at the time of power-shiftable loads in home buildings. According to the research, they represent 61% of residential energy consumption in UK and Canada, and 43% in USA [1]. Devices such as TVs, refrigerators, washing machines we use in day-to-day life and are able to communicate with each other that all credit goes to Machine to Machine (M2M) and Internet of Things (IoT) technologies.

HVAC systems are delivering comfort to the humans in their buildings indoor environment; hence, they are having huge demand and their automated development can ease the work of their users.

Recently, we have become more and more aware of the concepts of smart city such as smart home, transportation, health, education, energy and smart environment. In contrast, thermoelectric cooling offers a solid-state alternative that eliminates the need for moving components and harmful refrigerants. The thermoelectric effect enables direct conversion of electrical energy into a temperature gradient, thereby simplifying system architecture. Despite lower efficiency compared to traditional systems, thermoelectric modules offer advantages in terms of compactness, reliability, and precise temperature control. The integration of IoT technology into HVAC systems further enhances functionality by enabling remote monitoring, automation, and data-driven optimization. In this work, an STM32-based embedded system is combined with a thermoelectric cooling unit and wireless communication module to develop a smart HVAC prototype capable of autonomous operation and user interaction.

II. THEORETICAL BACKGROUND: THERMOELECTRIC COOLING

Thermoelectric cooling is based on the Peltier effect, a phenomenon discovered by Jean Charles Athanase Peltier in 1834. When an electric current flows through a junction of two dissimilar semiconductor materials, heat is absorbed at one junction and released at the other. The rate of heat transfer in a thermoelectric module can be expressed as:

$$Q_c = \alpha I T_c - \frac{1}{2} I^2 R - K(T_h - T_c)$$

The first term represents useful cooling due to the Peltier effect, while the second term accounts for Joule heating losses and the third term represents heat backflow due to thermal conduction.

The performance of a thermoelectric module is typically evaluated using the Coefficient of Performance:

$$COP = \frac{Q_c}{P_{\text{input}}}$$

Although the COP of thermoelectric systems is lower than that of conventional refrigeration, proper thermal management especially efficient heat dissipation on the hot side as can significantly enhance performance.

Thermal Resistance and Heat Dissipation

A critical factor influencing thermoelectric performance is thermal resistance. The hot-side temperature $T_h$must be minimized to maintain a high temperature gradient (T_h−T_c). The thermal resistance of the heat sink is given by:

$$R_{th} = \frac{T_h - T_{ambient}}{Q}$$

Efficient heat dissipation using high-conductivity materials (e.g., aluminum or copper heat sinks) and forced convection significantly enhances cooling performance.

III. SYSTEM ARCHITECTURE

The proposed system is structured as a multi-layer integrated architecture combining thermoelectric cooling, embedded control, and IoT-based communication. The design follows a closed-loop feedback mechanism to ensure adaptive thermal regulation under varying environmental conditions.

At a system level, the architecture follows a closed-loop control structure in which environmental temperature acts as the primary feedback variable. The temperature sensor continuously monitors ambient conditions and transmits digital data to the microcontroller. Based on this input, the control unit dynamically regulates the power supplied to the thermoelectric module via a switching device.

Simultaneously, the IoT module establishes a communication interface between the physical system and a remote user platform, enabling supervisory control and performance monitoring. The interaction between these subsystems ensures that the cooling process is adaptive, energy-aware, and remotely accessible.

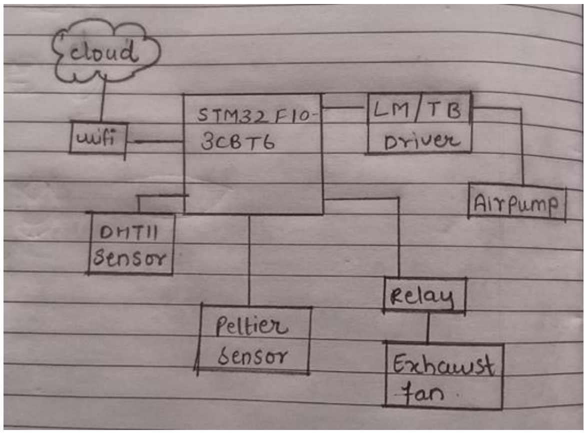
The thermal management layer is responsible for the physical heat transfer process and is the core of the HVAC functionality. It consists of the thermoelectric module, cold-side heat exchanger, hot-side heat sink, and forced convection fans.

The thermoelectric module operates by transferring heat from the cold junction to the hot junction when a DC current is applied. The cold side is exposed to the conditioned air channel, where it absorbs heat from the incoming air stream. The cooled air is then circulated into the target environment.

The temperature sensor, typically a digital sensor such as DS18B20, provides high-resolution temperature measurements. These readings are periodically sampled and processed by the microcontroller. The control algorithm compares the measured temperature with a predefined setpoint and determines whether cooling is required.

The thermoelectric module is driven through a power MOSFET, which acts as a switching and modulation device. Due to the high current requirements of the module, direct interfacing with the microcontroller is not feasible. Therefore, the MOSFET serves as an interface that allows the microcontroller to control high-power loads using low- power signals.

The communication layer enables the integration of the HVAC system with IoT platforms. A Wi-Fi module is used to establish connectivity with a cloud server or mobile application. The microcontroller communicates with the Wi-Fi module using serial communication protocols such as UART.



IV. LITERATURE REVIEW

The development of alternative cooling technologies has gained significant attention in recent years due to increasing environmental concerns and the limitations associated with conventional vapor-compression refrigeration systems. Thermoelectric cooling, based on solid- state heat transfer mechanisms, has emerged as a promising solution for small-scale and localized cooling applications. Numerous studies have explored the performance characteristics, material optimization, and integration of thermoelectric systems with modern control techniques.

Early work by Rowe [1] provided a comprehensive foundation for thermoelectric materials and devices, emphasizing the importance of the figure of merit (ZT) in determining system efficiency. The study highlighted that the performance of thermoelectric modules is highly dependent on material properties such as Seabeck coefficient, electrical conductivity, and thermal conductivity. However, achieving an optimal balance among these parameters remains a significant challenge.

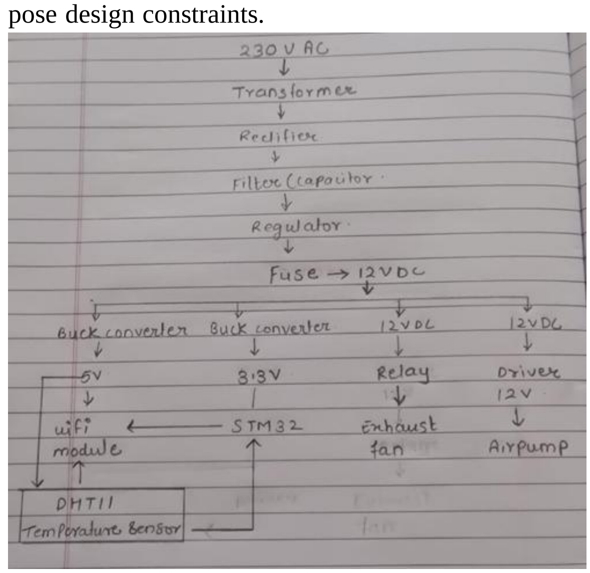
Min and Rowe [2] investigated the cooling performance of thermoelectric devices under varying electrical and thermal conditions. Their findings demonstrated that the efficiency of thermoelectric coolers is strongly influenced by operating current and thermal boundary conditions. The study concluded that improper heat dissipation at the hot side leads to a rapid decline in cooling performance, emphasizing the need for efficient heat sink design.

Lineykin and Ben-Yaakov [3] presented an analytical model for thermoelectric coolers, focusing on electrical and thermal interactions within the device. Their work provided insights into the nonlinear behavior of thermoelectric systems and proposed methods for optimizing operating conditions. The authors also highlighted the importance of dynamic control strategies for improving system efficiency.

In recent years, research has shifted toward the integration of thermoelectric systems with embedded control and IoT technologies. Kumar et al. [4] proposed an IoT-based HVAC monitoring system that enables real-time data acquisition and remote control. Although the study primarily focused on conventional HVAC systems, it demonstrated the potential of IoT in enhancing system intelligence and user interaction.

Further advancements have been made in combining thermoelectric cooling with microcontroller-based control systems. Studies have shown that the use of embedded platforms allows precise regulation of cooling performance through techniques such as pulse-width modulation (PWM). This approach not only improves energy efficiency but also extends the operational life of thermoelectric modules.

Despite these advancements, several challenges remain. Thermoelectric systems generally exhibit lower coefficient of performance (COP) compared to traditional refrigeration systems, limiting their application in large-scale cooling. Additionally, high power consumption and heat dissipation requirements pose design constraints.

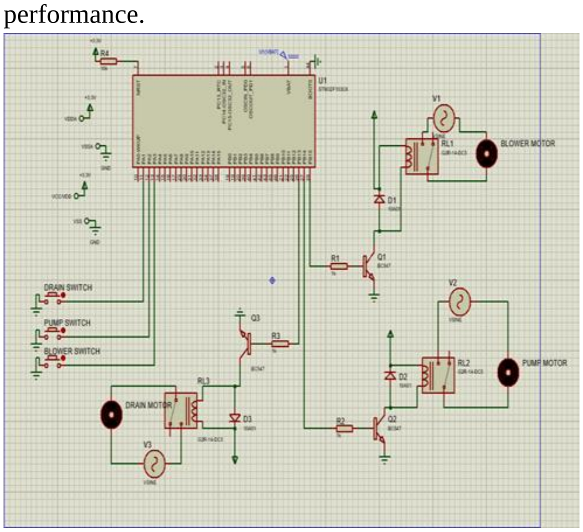


The present work builds upon these existing studies by integrating thermoelectric cooling with an IoT-enabled embedded system to develop a compact and intelligent HVAC prototype. Unlike previous approaches, this system focuses on real-time adaptive control, efficient thermal management, and remote monitoring.

V. WORKING PRINCIPLE

The system operates by continuously sensing the ambient temperature using a digital temperature sensor. When the measured temperature exceeds a predefined threshold, the control unit activates the thermoelectric module. The flow of current through the module initiates heat transfer, causing one surface to become cold and the opposite surface to become hot.

Air from the environment is directed over the cold surface, where it loses heat and is subsequently circulated into the conditioned space. Simultaneously, the hot side of the module dissipates heat through a heat sink and fan arrangement. The effectiveness of cooling is highly dependent on the efficiency of heat removal from the hot side, as inadequate dissipation leads to reduced temperature gradients and diminished performance.



The hardware implementation focuses on achieving efficient thermal management and reliable electronic control. The thermoelectric module used in this system operates at 12 V and requires a current of approximately 5–6 A, necessitating the use of a high-current switching device.

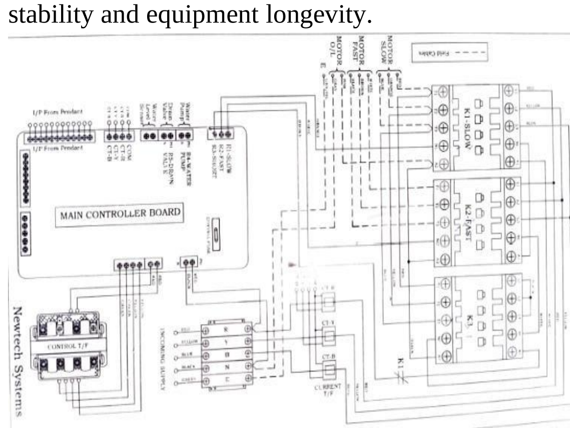
The STM32 microcontroller serves as the central processing unit, responsible for sensor data acquisition, control logic execution, and communication with the IoT module. The DS18B20 temperature sensor provides accurate digital readings, minimizing noise and calibration errors. A regulated power supply ensures stable operation of all components.

VI. INDUSTRIAL RELEVANCE AND APPLICATION

The proposed IoT-based thermoelectric HVAC system is designed with a strong emphasis on industrial applicability, particularly in scenarios where conventional cooling systems are either impractical or inefficient. In modern industrial environments, there is an increasing demand for compact, reliable, and maintenance-free cooling solutions for localized thermal management.

Thermoelectric cooling systems are widely considered for applications such as electronic enclosure cooling, control panel temperature regulation, battery thermal management, and precision instrument cooling. In such environments, traditional HVAC systems are often unsuitable due to their size, complexity, and reliance on refrigerants.

The proposed system addresses these limitations by offering a solid-state alternative that operates without moving mechanical components, thereby reducing maintenance requirements and increasing system reliability. From an industrial perspective, the integration of IoT capabilities significantly enhances system functionality. Real-time monitoring and remote diagnostics enable predictive maintenance and reduce operational downtime. This is particularly relevant in automated manufacturing systems and smart factories, where continuous monitoring of environmental conditions is essential for process stability and equipment longevity.



VII. CONCLUSION

This work presents an IoT-enabled thermoelectric HVAC system that integrates solid-state cooling with embedded control and real-time connectivity. The proposed system eliminates refrigerants and mechanical complexity while enabling precise temperature regulation through feedback-driven control.

Experimental evaluation confirms that effective cooling performance is achievable for localized applications, with system efficiency strongly dependent on thermal management at the hot side. The incorporation of PWM-based control improves energy utilization, while IoT integration enables remote monitoring and although thermoelectric cooling exhibits lower efficiency compared to conventional systems, the proposed architecture demonstrates its viability for compact, intelligent, and environmentally sustainable HVAC solutions. Future improvements in thermoelectric materials and heat dissipation techniques are expected to further enhance system performance and scalability

REFERENCES

[1] J. Serra, D. Pubill, A. Antonopoulos, and C. Verikoukis, "Smart HVAC control in IoT: Energy consumption minimization with user comfort constraints," *The Scientific World Journal*, 2014.

[2] R. Carli, G. Cavone, S. Ben Othman, and M. Dotoli, "IoT based architecture for model predictive control of HVAC systems in smart buildings," Sensors, vol. 20, no. 3, p. 781, 2020.

[3] A. M. Ali, S. A. Abdul Shukor, N. A. Rahim, Z. M. Razlan, Z. A. Z. Jamal, and K. Kohlhof, "IoT-based smart air conditioning control for thermal comfort," in Proc. IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS), IEEE, 2019, pp. 289–294.

[4] M. Taştan and H. Gökozan, "An Internet of Things based air conditioning and lighting control system for smart home," American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS), vol. 50, no. 1, pp. 181–189, 2018.

[5] B. Padmaja, V. Ch. Vijayakumar, E. Krishna Rao Patro, and B. Shashirekha, "A Smart IoT System for Remote Refrigeration Monitoring," 2021.

[6] M. N. A. Yusarelan, S. Z. A. Hamid, R. A. Rashid, and A. K. M. Ibrahim, "IoT Based Temperature Control for Smart Mosque," IOP Conference Series: Materials Science and Engineering, vol. 884, no. 1, p. 012079, 2020.

[7] Y. Huang, A. Khajepour, H. Ding, F. Bagheri, and M. Bahrami, "An energy-saving set-point optimizer with a sliding mode controller for automotive air-conditioning/refrigeration systems," Applied Energy, vol. 188, pp. 576–585, 2017.

[8] H. Jang, B. Kang, K. Cho, K. H. Jang, and S. Park, "Design and Implementation of IoT-based HVAC and Lighting System for Energy Saving," MATEC Web of Conferences, vol. 260, p. 02012, 2019.

[9] V. Patil, K. Bade, and Y. Bendale, "An Optimized use of Smart Air Conditioner using Cognitive IoT," Gandhi Institute for Education and Technology (GIET) Baniatangis, pp. 13–19, Mar. 2018.