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Integration of Temperature and Power Data Acquisition Using Modbus RTU RS485 Communication for Performance Monitoring of Thermoelectric Cooler Box

I Komang Sujana[1] Adi Winarta[2*]
[1] Program Studi Sarjana Terapan Teknologi Rekayasa Utilitas (TRU), Politeknik Negeri Bali, Badung, 80364, Indonesia
[2] Department of Mechanical Engineering, Politeknik Negeri Bali, Badung, 80364, Indonesia

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ABSTRACT

This study presents the design and implementation of a real-time data acquisition and monitoring system for a thermoelectric cooler box integrated with Phase Change Material (PCM) for thermal storage. The novel contribution of this research is the combined use of Modbus RTU RS485-based communication and real-time SCADA logging, enabling simultaneous monitoring of thermal and electrical performance. At the core of the system is the Haiwell SCADA application, which provides a user-friendly interface for continuous data visualization, logging, and fault detection. During the configuration phase, Modbus Poll is used to assign IP addresses and ensure communication integrity among the devices. The hardware setup consists of a laptop interface, an RS485 hub, and multiple slave devices, including thermocouples, NTC sensors, and power meters, all interconnected via structured wiring. Real-time power monitoring using PZEM-017 modules confirmed stable electrical performance, with brief transient drops during resets or manual interventions that quickly stabilized, demonstrating system resilience. This integration supports transient event tracking, performance degradation analysis, and improved diagnostics over time. Additionally, the system enables detailed performance mapping, facilitating proactive maintenance and optimization of cooling performance under varying loads.

Corresponding Author:

Adi Winarta
Department of Mechanical Engineering, Politeknik Negeri Bali, 80364, Indonesia
Email: adi.winarta@pnb.ac.id

1. INTRODUCTION

Automatic control in refrigeration systems is crucial for improving operational efficiency and maintaining consistent thermal performance. Efficiency and effectiveness are defined by stable cooling, minimal energy use to reach target temperatures, and sustained thermal stability during operation [1]. Vapor compression refrigeration, the dominant technology today, employs refrigerants like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), which, despite their efficacy, pose serious environmental risks such as ozone depletion and global warming [2]. Thermoelectric refrigeration systems, based on the Peltier effect, present an eco-friendly alternative. TECs provide solid-state cooling without moving parts or harmful chemicals, though they are less common than vapor compression systems. These systems suit applications requiring compact and environmentally safe cooling solutions [3].

Effective control and monitoring of refrigeration systems depend on reliable industrial communication protocols. MODBUS, initially developed for Modicon programmable controllers, is widely adopted due to its simplicity and flexibility across networks like MODBUS Plus, Ethernet, and MAP [4]. MODBUS RTU is prevalent in Building Management Systems and Industrial Automation, using a master-slave architecture over RS-485 for serial communication. It ensures data integrity through a 16-bit Cyclic Redundancy Check (CRC) and supports half-duplex communication over distances up to 1200 meters with up to 32 devices on one bus [4,5].

This study employs MODBUS RTU over RS-485 as the communication backbone in a real-time monitoring platform integrated with a hybrid thermoelectric cooler (TEC) and Phase Change Material (PCM) system. The system uses thermocouples to measure chamber temperature, Negative Temperature Coefficient (NTC) sensors for PCM interface monitoring, and power meters for energy consumption. Data is processed and visualized in real time through the Haiwell SCADA platform, which functions both as a user interface and data aggregator.

Haiwell SCADA leverages industrial-grade MODBUS RTU communication to facilitate robust and reliable sensor data collection. The platform's high-resolution acquisition, with sub-second logging intervals, enables detailed performance monitoring and early detection of anomalies under dynamic operational conditions. Integrating MODBUS RTU within this architecture demonstrates the feasibility of combining industrial protocols with smart monitoring tools to optimize compact refrigeration systems. This modular approach offers scalability, cost-effectiveness, and compatibility with open-source tools, supporting advanced analytics like predictive diagnostics and machine learning optimization. By combining TEC and PCM thermal management with MODBUS-based communication and SCADA monitoring, the study presents a novel embedded refrigeration system. Unlike conventional manual or limited digital monitoring, this system supports autonomous, energy-efficient operation in critical applications.

The objective of this study is to develop and evaluate an integrated monitoring platform capable of continuous data acquisition, analysis, and logging of key performance parameters of the TEC–PCM system. This platform supports sub-second response times for accurate temperature and power tracking, transient event detection, and performance recovery analysis critical for operational stability and fault tolerance. Continuous logging in structured formats enables further data analysis and system optimization [6]. This integrated approach highlights the potential of combining industrial communication protocols with intelligent monitoring to improve the reliability, energy efficiency, and adaptability of compact refrigeration technologies.

2. METHOD

This study aims to develop an integrated monitoring system for a thermoelectric cooler box equipped with Phase Change Material (PCM) for thermal storage, utilizing the Modbus RTU RS485 communication protocol to enable synchronized data acquisition from multiple devices.

The system comprises several key components: a Modbus RS485 plus TTL module interfaced with two Thermistor/Negative Temperature Coefficient (NTC) sensors (Device 1); an RS485 hub connecting two PZEM power monitoring modules (Devices 2 and 3); and two 8-channel K-type thermocouple modules (Devices 4 and 5). This modular setup facilitates simultaneous monitoring of temperature and power consumption parameters critical to evaluating system performance.

The methodology consists of three main stages: equipment preparation, hardware assembly, and software development. During equipment preparation, all sensors and communication modules were selected and calibrated to ensure measurement accuracy. The hardware assembly phase involved integrating sensors into the Modbus communication network, establishing electrical connections, and verifying signal integrity. In the software development stage, two software platforms were used: Modbus Poll, which served to identify and verify the Modbus addresses and function codes of all connected devices, and Haiwell SCADA, which was utilized for real-time data acquisition, visualization, and logging. Haiwell SCADA acted as the main supervisory interface, enabling centralized monitoring and control of the entire system via Modbus RTU protocol over RS-485. These tools ensured robust communication, accurate data mapping, and seamless integration of field devices with the SCADA platform.

The integrated system monitors the thermoelectric cooler box's internal environment and energy consumption to assess overall operational efficiency. Figure 1 presents the Monitoring setup schematic showing sensor-to-module connectivity via Modbus RTU RS485. The thermoelectric cooling system, as depicted in Figure 2, includes Thermoelectric Coolers (TECs), PCM, and a closed-loop liquid cooling circuit designed to maintain low internal temperatures within the cooler box. Power sources to thermoelectric were controlled by thermocontroller digital. The cut-off and cut in of thermocontroller were determined from the temperatures of PCM. Two thermistors were inserted into PCM containers. The cold sink, thermally coupled with the TEC module, extracts heat from the box interior, where a drinking water bottle is stored. A circulation fan ensures uniform cooling throughout the interior space.

The hot side of the TEC is managed by a water-cooling block, forming part of a closed-loop liquid cooling system. Water is introduced via an inlet pipe monitored by a flow meter, passes through the cooling block where it absorbs heat, and is then pumped into a radiator equipped with dual fans. The cooled water is finally recirculated into the reservoir tank, completing the cycle.

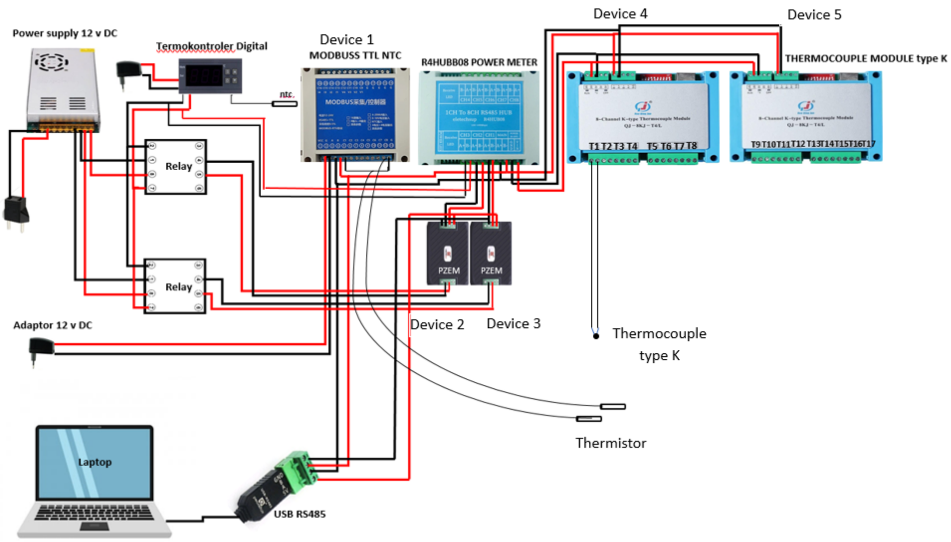

Figure 1. Schematic: sensor-module Modbus RTU RS485 links.

To obtain comprehensive thermal data, 17 sensor temperatures (T1 to T17) were installed at key positions throughout the system. Thermocouples T1 and T3 monitor the water temperature entering the cooling block, while T2 and T4 track the outlet temperature. T5 and T6 measure temperatures on the cold side of the TEC to assess its cooling performance. Within the cooler box, T7 is placed near the cold sink, T8 and T9 are located around the beverage bottle, and T10 and T11 record ambient internal air temperature. For system-level monitoring, T12 observes water temperature near the flow meter, and T13 tracks temperature along the tubing connecting the TEC to the radiator.

This systematic approach, supported by reliable communication protocols and industrial-grade software tools, enables real-time performance monitoring of the thermoelectric cooling system. It facilitates high-resolution data acquisition and supports further analytical evaluations such as energy consumption profiling, cooling efficiency analysis, and thermal management optimization.

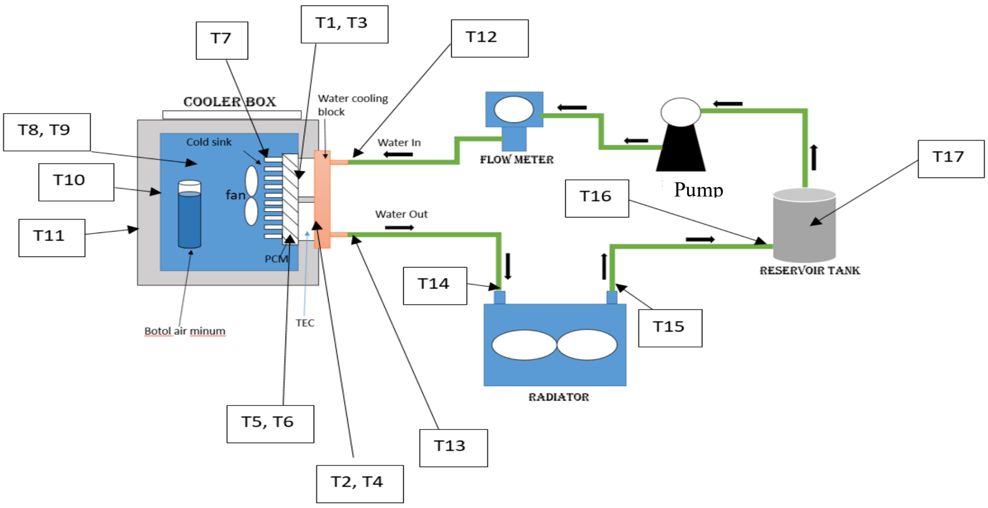

Figure 2. Placement of temperature sensors

3. RESULTS AND DISCUSSION

The configuration of each device was performed with detailed attention to communication parameters. Below are the tables summarizing the configurations for the various measurement devices (Table 1). Once the sensor modules were configured and integrated with the Modbus RTU communication system, the system was tested using the Modbus Poll software. This initial step ensured that the sensors were correctly reading and transmitting data to the SCADA system. Subsequently, the Haiwell SCADA system was employed for real-time data visualization, offering a comprehensive dashboard that displayed temperature and power consumption in graphical form.

Table 1. Configurations of the Modbus protocol in system for each measuring devices.

Host Name	Device 1 (Modbuss Thermistor /NTC)	Device 2 (PZEM-017)	Device 3 (PZEM-017)	Device 4 (Module of thermokopel type K)	Device 5 (Module of thermokopel type K)
Conection	Serial port	Serial port	Serial port	Serial port	Serial port
Port	Com 2	Com 2	Com 2	Com 2	Com 2
Baudrate	9600	9600	9600	9600	9600
Data Bits	8	8	8	8	8
Stop bits	2	2	2	2	2
Parity	None Parity	None Parity	None Parity	None Parity	None Parity
IP Address	127.0.01	127.0.01	127.0.01	127.0.01	127.0.01
Mode	RTU	RTU	RTU	RTU	RTU
Slave ID	1	2	3	4	5
Address Mode	Dec	Dec	Dec	Hex	Hex
Function	04 Read Holding Register (4X)	04 Read Input Register (3X)	04 Read Input Register (3X)	03 Read Holding Register (4X)	03 Read Holding Register (4X)
Address	0	0	0	64	64
Quantity	2	3 (Volt, ampere, watt)	3 (Volt, ampere, watt)	8	8
Scan rate	1000	1000	1000	1000	1000

The SCADA system provided a real-time view of the cooler box's performance, allowing operators to monitor temperature fluctuations and power usage over time. The system's dashboard displayed both the temperature readings and power consumption data, ensuring that all relevant parameters were being monitored simultaneously.

3.1. Temperature Monitoring Results

The primary objective of the monitoring system was to evaluate the temperature performance of the thermoelectric cooler. The temperature sensors successfully captured data from multiple points within the cooler box, providing a detailed temperature profile. Figure 3 illustrates graphical dashboard for temperature data logging and visualization in Haiwell SCADA. The temperature sensor reading is visualized with Figure 3a, 3b and 3c for thermistors and thermocouples. Figure 4 shows the temperature history from various thermocouple sensors positioned throughout the thermoelectric cooling system, including inlet and outlet water channels, the cold and hot sides of the TEC module, the cooler box interior, and around the PCM, providing a comprehensive overview of thermal dynamics during system operation. The PCM effectively absorbed excess heat during the cooling phase and maintained the desired temperature once the thermoelectric cooler powered off, demonstrating the importance of integrating thermal storage in thermoelectric cooling systems.

3.2. Power Consumption Monitoring Results

Figure 3d shows dashboard for displaying power consumption data. Figure 5 shows the power consumption graph showing voltage, current, and power over time. The power consumption data, obtained from the PZEM 017 power meters, revealed that the thermoelectric cooler consumed energy during the cooling process but reduced its power consumption once the target temperature was achieved. This dynamic energy usage pattern demonstrates the energy efficiency of the cooler, with the PCM serving as a key factor in minimizing energy consumption during the stabilization phase.

3.3. Data Integration and Historical Data Reporting

The integration of both temperature and power consumption data into a single SCADA platform allows operators to monitor the system's performance seamlessly. Additionally, the system supports historical data reporting, enabling the collection and storage of data at regular intervals for long-term analysis. This capability is particularly useful for evaluating system performance over extended periods, allowing for the identification of trends and potential areas for improvement. The system demonstrated effective temperature and power monitoring of the thermoelectric cooler box, highlighting the critical role of phase change material (PCM) in stabilizing the internal temperature. The integration of multiple sensors allowed for detailed data collection at various critical points, ensuring that all aspects of the cooler box's performance were monitored.

The power consumption data indicated that the system operates efficiently, using energy only when necessary to achieve and maintain the desired temperature. The real-time data visualization and historical reporting features of the SCADA system provided valuable insights into the cooler's performance, making it easier for operators to track energy usage and temperature changes over time.

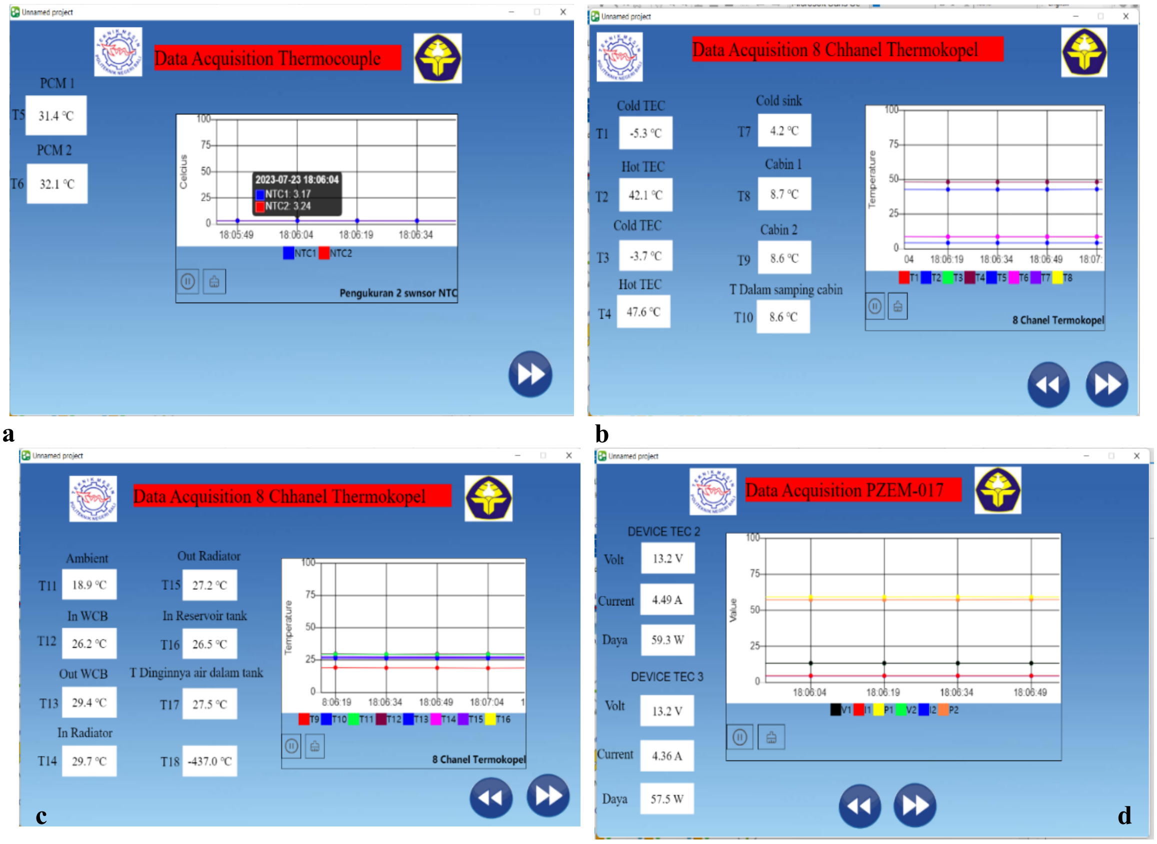

Figure 3. Graphical dashboard for temperature data logging and visualization in Haiwell SCADA.

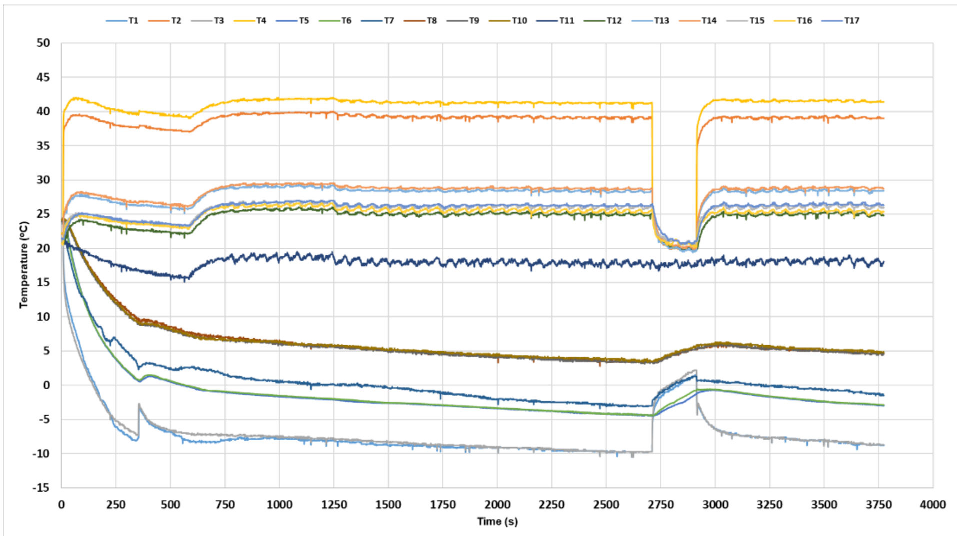

Figure 4. Time series for temperatures data of thermoelectric cooler box for each sensors.

The integration of Modbus RTU RS485 communication protocol with various sensor modules ensured seamless data acquisition and reliable performance monitoring. The results of this study demonstrate the potential of this monitoring system for optimizing the performance of thermoelectric coolers, offering a valuable tool for energy efficiency and system management. In summary, the combined use of TEC, PCM, and water-cooling with an integrated real-time monitoring system has demonstrated promising performance in maintaining cold storage temperatures. The data acquisition and SCADA integration also prove critical in capturing transient thermal behaviors, ensuring continuous system reliability and enabling further optimization based on monitored trends [7]. Future work may focus on several key areas to enhance system capability and applicability, such as: (1) integration with photovoltaic-based renewable systems to increase energy autonomy, (2) development of adaptive control algorithms for dynamic load and temperature regulation, and (3) scalability for multi-zone thermal management applications in more complex cooling environments.

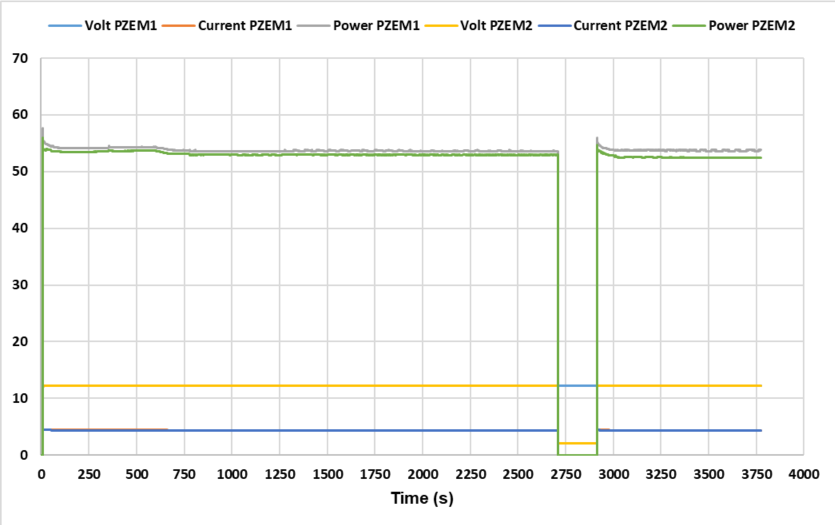

Figure 5. Power meter graphic result

4. CONCLUSION

This study successfully demonstrated the integration of temperature and power measurement systems using the Modbus RTU RS485 communication protocol for monitoring the performance of a thermoelectric cooler box equipped with Phase Change Material (PCM) as thermal storage. Through the deployment of TEC modules, PZEM-017 power meters, NTC sensors, and K-type thermocouples combined with the Haiwell SCADA platform real-time data acquisition and monitoring were effectively achieved. The application of Haiwell SCADA provided a user-friendly interface for continuous monitoring, rapid diagnostics, and real-time data logging, enabling the system to respond effectively to thermal and electrical variations. This research contributes to the development of compact, intelligent, and environmentally friendly refrigeration systems, offering potential for broader adoption in energy-sensitive cooling applications such as biomedical storage, portable refrigeration, and solar-powered systems. Overall, the system demonstrates a robust, adaptable, and scalable solution for sustainable thermal energy management.

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