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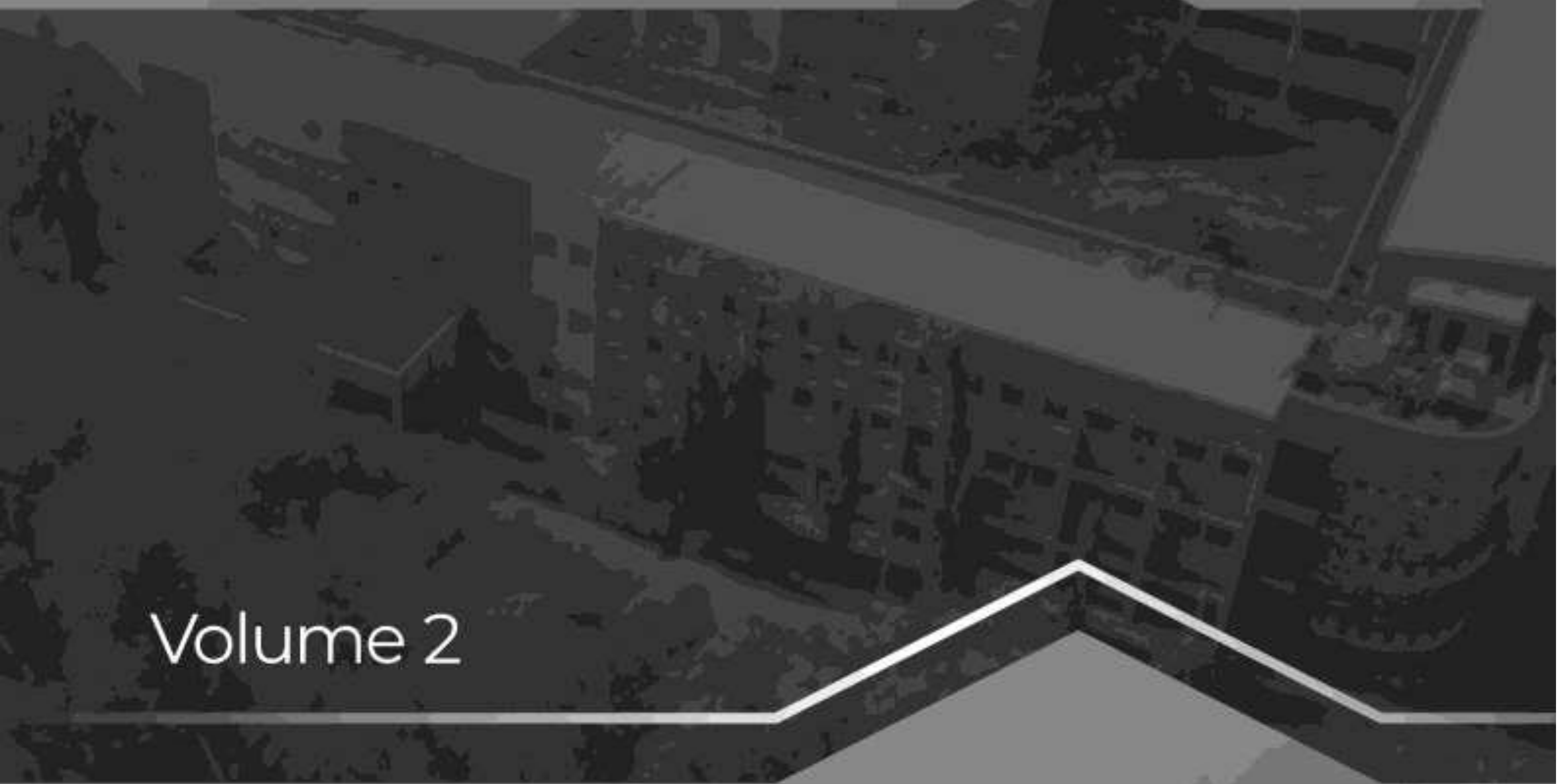

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Thermal Comfort Performance of Thermoelectric Peltier Module Refrigeration System in Built Environment

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Abstract

According to data provided by the International Energy Agency, nearly 1.6 billion air conditioning (A/C) systems were operating globally in 2017, accounting for approximately 6% of the overall final energy consumption. To address the energy and economic challenges posed by such extensive use of air conditioning for thermal comfort, it is imperative to identify alternative solutions that can effectively operate in warm-humid environments. This study explored the thermal comfort performance of thermoelectric module refrigeration (TEMR) system in built environment; installed in a single-room facility in Minna, Niger State, Nigeria, over a one-month period. The experimental setup involved a test room measuring 1.3 m x 2.6 m x 3 m, equipped with aluminum roofing, an asbestos ceiling, an aluminum-framed window, and a steel door. The TEMR system was assessed for its ability to regulate indoor temperature and humidity under varying external climatic conditions. The TEMR system operated at a constant current of 6.4A, with data collected at specific intervals throughout each day. Results indicated that the TEMR system significantly reduced indoor air temperature and relative humidity, particularly during peak operational hours (12:00 pm to 2:00 pm). Weekly variations showed temperature drops from 37°C to 22°C and humidity reductions from 60% to 32% within 60 minutes of operation. These findings align with ASHRAE Standard 55-2017 for indoor environmental quality. The study concludes that the TEMR system is effective in improving indoor climatic conditions, offering a sustainable and energy-efficient cooling solution. Its performance, influenced by external climatic factors, demonstrates potential for broader application, particularly in developing regions where long-term, low-maintenance, and environmentally friendly cooling solutions are needed.

Keywords: Keywords: Air Conditioned, Refrigeration, Thermal Comfort, Thermoelectric.

1. Introduction

The global surge in population necessitates the exploration of new energy sources that are both environmentally friendly and technically efficient. In hot-dry regions, the prevalence of air conditioning (A/C) systems is a direct response to the intense heat and dry climate, essential for achieving indoor comfort (United Nations Department of Economic and Social Affairs UN DESA, 2022; International Energy Agency IEA, 2023; Saidur *et al.,* 2023). Thermal comfort, defined as the human satisfaction with the thermal environment, hinges on inhabitants' thermal sensations (ASHRAE 55 - 2020). Yang and Moon (2018) further describe thermal comfort as a psychological condition influenced by past experiences and adaptability. The demand for modern, maintenance-free energy systems to replace outdated installations is rising. Scientists and engineers are dedicated to developing efficient heating and cooling energy systems, driven by the growing energy needs and advancements in engineering sciences (Jackson *et al.,* 2018; Van-Ruijven *et al.,* 2019). The International Energy Agency (2019) reported that approximately 1.6 billion A/C units operated globally in 2017, consuming about 6% of the total final energy, underscoring the need for alternative solutions to tackle energy and economic crises. Thermoelectric modules (TEMs) offer a promising alternative. These solid-state energy converters can generate a temperature difference using electric potential (Peltier effect) or generate electricity from a temperature difference (Seebeck effect) (Enescu and Virjoghe, 2014). Thermoelectric refrigeration, based on the Peltier effect, functions as a small heat pump, moving heat through the module when powered by a low voltage direct current (Wang and Zhang, 2023). This technology can be applied in various cooling scenarios, including refrigeration and down-hole measuring equipment (Huang and Zhang, 2022). As energy efficiency in buildings becomes crucial due to rising concerns over CO2 emissions and fossil fuel scarcity, the thermal performance of building envelopes significantly impacts cooling energy consumption (Liu and Liu. 2023; Chen and Yang, 2024). This study aims to assess the thermal comfort performance of thermoelectric Peltier module refrigeration systems in built environments. It investigates the advantages and disadvantages of existing HVAC systems, the impact of thermoelectric refrigeration on indoor air conditions, and the cooling power output in an experimental test room.

2. Literature Review

2.1 Reviews on Existing Heating Ventilation Air Conditioning (HVAC) Systems

Energy consumption in commercial and residential sectors is projected to increase annually by 0.5% and 0.8%, respectively, from 2013 to 2040 (US Energy Information Administration, 2015; Lee and Park, 2023). HVAC systems are significant energy consumers in these sectors, accounting for approximately 43% of energy use in buildings. Consequently, demand-driven control in HVAC systems has become essential, with occupancy-based control being a critical factor in reducing energy consumption. Advanced systems and techniques utilizing statistical and probabilistic models for occupancy detection and prediction are being explored (Zhao and Li, 2023; Kumar and Ahuga, 2024).

2.2 Thermoelectric Refrigeration System

Cooling devices account for nearly 20% of global electricity consumption in buildings, with space cooling energy use expected to rise significantly by 2050 (Birol, 2018). Traditional air conditioners contribute to urban heat islands and greenhouse gas emissions due to the use of hydrofluorocarbon refrigerants (Cao, 2016; McLinden *et al.*, 2017; Smith and Brown; 2023). Thermoelectric cooling, leveraging the Peltier effect, offers an alternative with advantages like compact size, quiet operation, and reduced environmental impact. Despite its lower coefficient of performance (COP) compared to vapor compression systems, thermoelectric cooling's benefits, including no refrigerants and reliable temperature control, make it promising for niche applications (Ibañez-Puy *et al.*, 2017; Wang and Lin, 2023; Zhang and Zhang, 2024).

2.2.1 Heat sink design and performance

Effective heat dissipation is crucial for thermoelectric devices. Heat sinks, typically made of aluminum, are essential for maintaining performance by transferring heat from the hot side of the thermoelectric module. Designs vary from natural convection, suitable for low power applications, to forced convection and liquid cooling for higher efficiency. Optimal designs must balance thermal resistance and airflow to prevent overheating (Liu and Zhang, 2023; Zhou and Zhao, 2024).

2.2.2 Applications of thermoelectric refrigeration

Thermoelectric cooling finds use in specialized fields due to its reliability and compact design. Applications range from domestic portable refrigerators to medical devices for temperature control in therapeutic settings, automobile mini refrigerators, and cooling systems for electronic components and scientific equipment (Li and Zhang, 2024; Sun and Chen, 2024). Despite its lower COP, technological advancements continue to expand its potential applications.

3. Materials and Methods

3.1 Materials Description

The Thermoelectric Refrigeration System utilized in this experiment comprises various components as detailed in Table 3.1:

Table 3.1: Performance Specifications of Experimental Materials

S/N	Equipment	Type	Quantity	Function	Specification
1	Peltier Module	TEC1-12706	5	Create temperature gradient	Qmax: 52-57 W, ΔTmax: 66-75 °C, Imax: 6.4 A, Vmax: 14.4-16.4 V, Resistance: 1.98-2.30 Ω
2	Heatsinks (Cross-fin)	Finned aluminum	5	Enhance heat dissipation	Density: 2.71 g/cm^3, Thermal conductivity: 202 W/m-K
3	Axial/Blower Fans	12V DC	-	Circulate air	-
4	Dry Cell Rechargeable Battery	SN12-7.5	1	Power source for TEMs	12V, 7.5AH/20HR, Initial current: 2.25 A max
5	Digital LCD Electronic Alarm Clock Hygrometer	HTC-1	1	Measure indoor weather	Temp accuracy: ±0.1°C

3.1.1 Peltier module

The Peltier Module, operating on the Peltier effect, creates a heating and cooling effect at the junction of two different conductors when electric current flows through. The heat generated at the junction (Peltier Heat) is given by

$$Q = (\Pi_A + \Pi_B) \times I \qquad (I)$$

where Π_A and Π_B are the Peltier coefficients of the conductors, and I is the current.

Plate I: Peltier module

3.1.2 Heat sink

Heat sinks, typically made of conductive metals like aluminum or copper, dissipate heat from high-temperature components. Finned designs increase surface area for better heat transfer (Chen and Yang; 2023; Huang and Li, 2024).

Plate II: Heatsink

3.1.3 Blower fan

Blower fans provide active cooling by drawing cool air into the system and expelling warm air. These fans, usually operating on 12V DC, can ventilate large areas effectively. It can be used to ventilate up to 1,250 square feet (116 m^2) of area and can move air at up to 800 cubic feet per minute (400 L/s).

Plate III: Model of axial/blowerfans (12V DC)

3.1.4 Dry cell rechargeable battery

A DC device, the thermoelectric module, is powered by a rechargeable battery, allowing multiple charges and discharges. A rechargeable battery, storage battery, or secondary cell, (or archaically accumulator) is a type of electrical battery which can be charged, discharged into a load, and recharged many times, as opposed to a disposable or primary battery, which is supplied fully charged and discarded after use.

Plate IV: Dry cell rechargeable battery

3.1.5 Digital LCD electronic alarm clock hygrometer

This device monitors indoor temperature and humidity, offering high precision and low power consumption. It can record the highest and lowest temperature/humidity, set a daily alarm, and display time/temperature/humidity with a wide temperature measuring range from -58°F to 158°F; a humidity measuring range from 20% to 99% RH.

Plate V: Digital LCD electronic alarm clock hygrometer

3.2 Methods

Thermoelectric Assemblies (TEAs) were used for heating and cooling, with heat sinks to dissipate heat from the TEC. Theoretical performance equations for the TEC include

Voltage, $V = \propto(T_H - T_L) + IR)$ (2)

Input power $(P = \propto I(T_H - T_L) + I^2R)$ (3)

Cooling capacity $Q_L = I\propto T\_C(T_H - T_L) - 0.5I^2R)$. (4)

The cooling load calculation is given by Refrigeration Effect = $(m \times C_\rho \times \Delta T) / t$. (5)

3.2.2 Selection of Thermoelectric Modules

Parameters such as mass of indoor air, specific capacity, and temperature difference determined the number of modules required. The cooling capacity was measured in British Thermal Units (BTU), with calculations showing five TEC1-12706 modules were ideal for the test room dimensions (2.6 m x 1.3 m x 3.0 m). The assembled system was tested before mounting in the experimental setup.

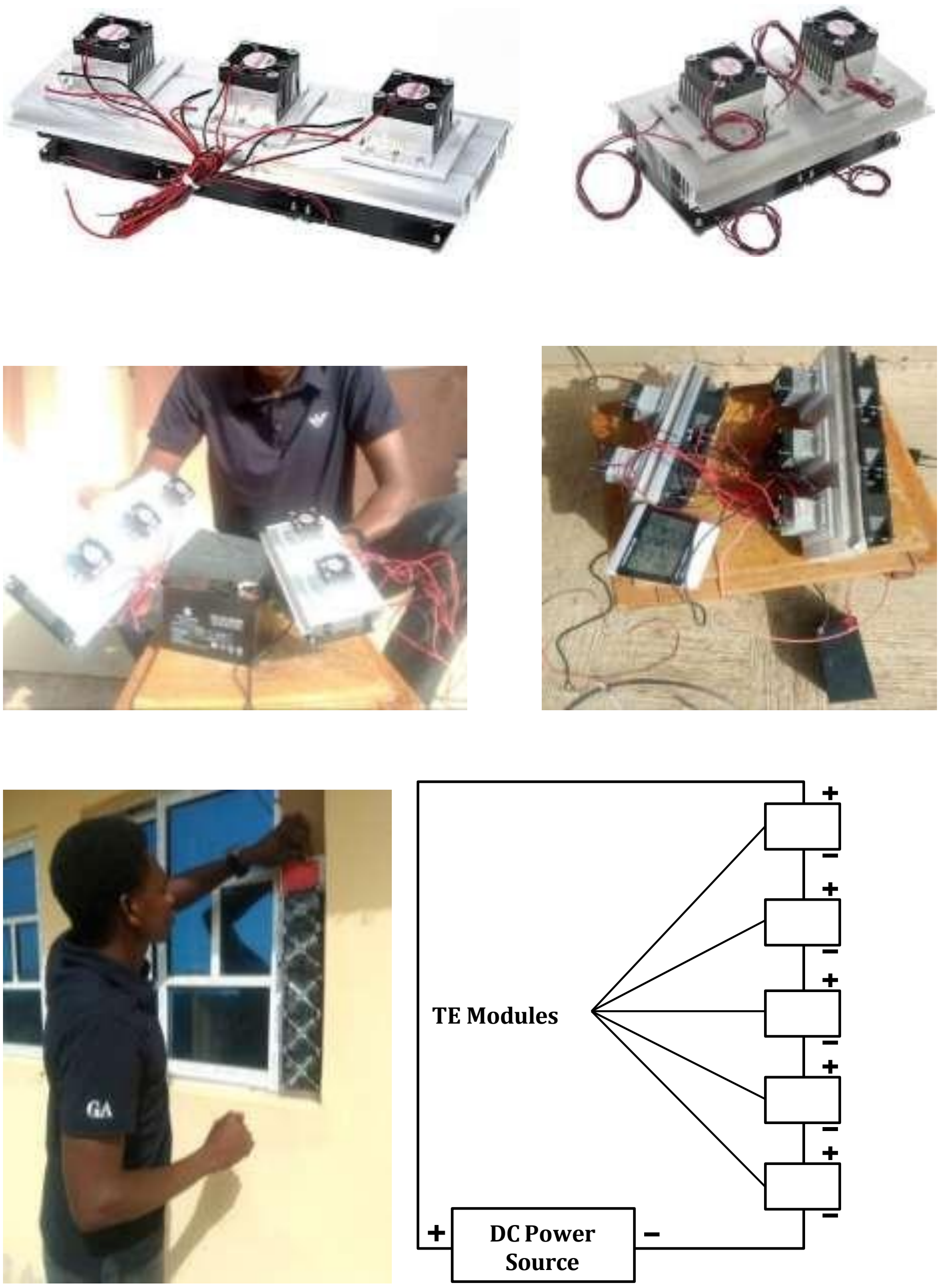

Plate VI: Show the assembly and installation of the Thermoelectric Refrigeration system

4. Results and Discussion

The experiment and data collection took place in a single-room house equipped with the thermoelectric refrigeration system in Minna, Nigeria (26° 32' N, 50° 13' E). The test room dimensions were 1.3 m x 2.6 m x 3 m, with an aluminum roof and asbestos ceiling.

4.1 Effects on Indoor Air Temperatures and Relative Humidity

The TEMR system operated at 6.4A during specified hours. Surface temperature changes indicated one side becoming hot and the other cold. Data recorded per ASHRAE Standard 55-2017 showed temperature and humidity differences were most significant during peak hours (12:00 pm - 2:00 pm). The system effectively reduced indoor temperature and humidity, with peak performance observed in the first week of operation (Figures 4.1 to 4.4).

4.2 On-Site Measurement Effect of the TEMR System on Room Temperature

As described above, study was carried out in a hot humid climate in the city of Minna, where outdoor temperatures and relative humidity were high. Due to the geographical location, there was no seasonal change, so, values usually fluctuate very little through the month of November. The average values for indoor air temperature (T_{a_indoor}) and indoor relative humidity (RH_{indoor}) were measured in each field test carried out for the purpose of this study. Therefore, the effect of implementing the TEMR system on indoor operative temperature and relative humidity of the test room at different time interval with input current supply of 6.4 A to TEMR system is presented in Figure 4.1 to 4.4.

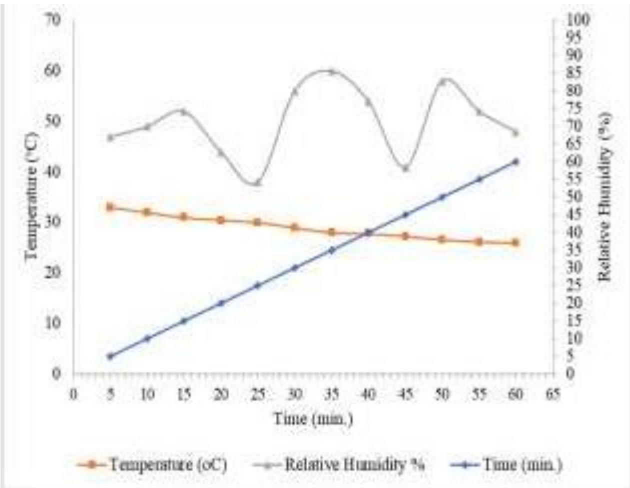

Figure 4.1: First week variation of indoor climatic conditions of the test room with time, when TEMR system operated at

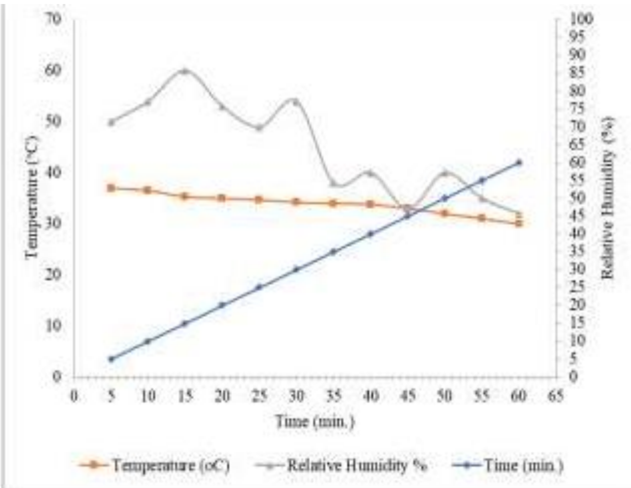

Figure 4.2: Second week variation of indoor climatic conditions of the test room with time, when TEMR system operated at 6.4A

Figure 4.1 shows the indoor climate variations over time in the test room with the TEMR system running. The indoor temperature dropped from 33°C to above 26°C in 60 minutes at 52W, with measurements taken every 5 minutes. The temperature and humidity fluctuations correlate with the cooling load and current draw of the TEMR components. The ideal indoor conditions were 27.3°C and 41% humidity at 45 minutes, which aligns with ASHRAE 55 (2017) standards for thermal comfort. Initially and finally, relative humidity was higher but decreased as the temperature dropped during peak hours. Figure 4.2 displays similar data for the second week, showing average temperature and humidity dropping from 37°C to 30°C and 60% to 32% respectively, within 60 minutes at 57W. Despite some fluctuations, the relative humidity was adequate, but temperatures were not ideal, influenced by high outside temperatures and humidity.

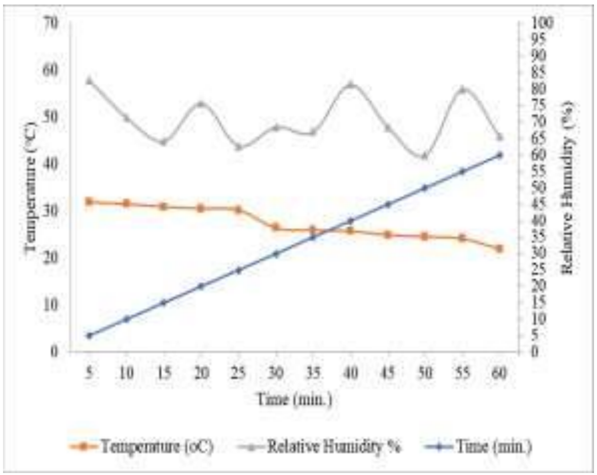

Figure 4.3: Third week variation of indoor climatic conditions of the test room with time, when TEMR system operated at 6.4A.

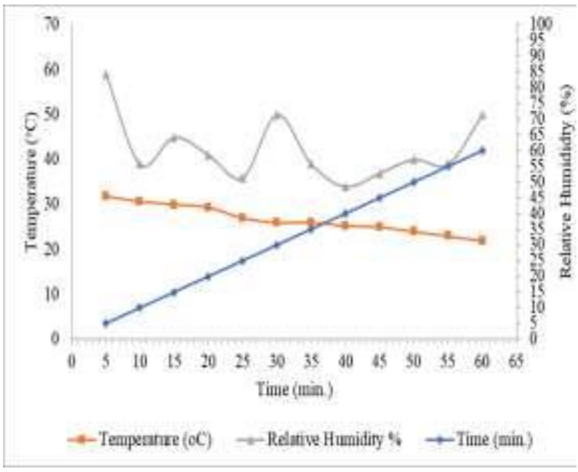

Figure 4.4: Forth week variation of indoor climatic conditions of the test room with time, when TEMR system operated at 6.4A.

Figure 4.3 shows the variation in indoor climate conditions over time in the test room with the TEMR system running. The indoor temperature dropped from 32°C to 22°C, and humidity fell from 58% to 42% within 60 minutes at 57W. The temperature and humidity decreased steadily over time, reaching a stable condition at 26.5°C and 48% after 30 minutes. Figure 4.4 depicts a similar trend, with indoor temperature dropping from 31.8°C to 22°C and humidity from 59% to 34% in 60 minutes at 52W. Despite some fluctuations, the conditions remained adequate, with the temperature and humidity stabilizing at 27°C and 36% after 25 minutes, aligning with ASHRAE 55 standards for thermal comfort.

4.3 Summary of Findings

The TEMR system demonstrated effective performance over the month, particularly during initial and final hours of operation. Peak operating hours saw high outdoor temperatures (above 37°C) and humidity (above 85%). The system, operating at 6.4A, achieved significant reductions in indoor temperature (4-5.7°C) and humidity (8-22%). The system's efficiency increased with higher heat pumping capacity on the cold side, which absorbed more heat from the ambient air, thus reducing the indoor temperature and humidity effectively. This performance aligns with the principles of thermoelectric cooling and the theoretical equations provided.

5. Conclusion and Recommendations

The experimental results indicate that the thermoelectric refrigeration system performs well under given conditions with forced air convection heat dissipation. A temperature reduction of 15°C was achieved in the test room from an ambient temperature of 37°C in 60 minutes. Given current energy and environmental challenges, thermoelectric refrigeration systems show promising potential for future thermoelectric generation and cooling, particularly in developing countries and remote areas where long life, low maintenance, and a clean environment are crucial. Environmentally, the thermoelectric refrigeration system is eco-friendly due to the use of the Seebeck module, which does not deplete the ozone layer. Technically, it is recommended for its high COP at low power input, reducing energy consumption. Optimizing the TER system's power operation is sustainable and advantageous over window air conditioners: it uses no chlorofluorocarbons, maintains precise temperature control, and offers flexible, small form factors. However, improving thermoelectric modules' conversion rate remains urgent for their commercialization.

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