Sustainable Residential Air Conditioning System

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Abstract. The proposed project focuses on the design and development of a sustainable residential air conditioning system using thermoelectric cooling (TEC) technology. Unlike conventional vapor compression systems, the TEC-based system operates without compressors or refrigerants, offering a compact, noiseless and eco-friendly solution. The prototype utilizes 35 TEC1-12715 modules arranged in series to provide effective cooling for a 3.048 m × 3.048 m × 3.048 m room. The heat sinks and forced convection fans ensure efficient heat dissipation, while the hot side heat can be recovered for applications such as water heating, further enhancing energy efficiency. The system's performance is evaluated in terms of temperature reduction, power consumption and Coefficient of Performance (COP), with results compared to conventional AC systems. The cooling COP is 5 and above for expected low temperature range of 2 to 10°C. The study demonstrates the feasibility of TEC modules for residential cooling, emphasizing energy efficiency, sustainability and potential integration with renewable energy sources such as solar power.

Keywords: Sustainable cooling; Coefficient of performance; Energy efficiency; Smart cooling.

1 Introduction

Thermoelectric cooling (TEC) technology is an emerging solid-state cooling method based on the Peltier effect, where the application of an electric current causes heat transfer from one side of a semiconductor module to the other [1]. TEC devices offer numerous advantages, including noiseless operation, lack of moving parts, compactness and environmental friendliness due to the absence of refrigerants and compressors commonly used in conventional vapor compression air conditioning systems. Traditional air conditioning systems, which primarily rely on vapor compression refrigeration cycles, dominate the market but face significant challenges. These include high electricity consumption, the use of environmentally harmful refrigerants contributing to greenhouse gas emissions and complex machinery with multiple moving parts necessitating regular maintenance. Additionally, growing

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concerns about climate change and energy efficiency have driven research towards alternative cooling technologies that can reduce carbon footprints and improve sustainability in buildings.

Thermoelectric modules generate a temperature gradient through solid-state semiconductor materials such as Bismuth Telluride. By controlling the direction and magnitude of the electric current, heating or cooling can be selectively achieved on different sides of the device [2].

In parallel, thermoelectric technology has found other innovative applications, such as multi-utility systems combining water heating and space cooling. A thermoelectric multi-utility water heater cum air-conditioner (TE-MUWH) system simultaneously heats tap water from ambient temperatures to desired setpoints while cooling indoor air, thus serving dual residential needs. This system has demonstrated substantial energy savings, reducing electrical power consumption and peak demand in residential settings [3]. The modular nature, lack of moving parts and long expected operational lifespan make such thermoelectric solutions attractive for sustainable residential energy management. Despite these promising developments, challenges remain in optimizing thermoelectric materials, module designs and heat exchange configurations to maximize cooling capacity and COP for broader adoption. TEC has advantages over other electronic devices, including its small size, low weight, and lack of working fluid, which reduce maintenance costs and enable easy switching between cooling and heating modes [4]. Advances in computational modeling, material science and experimental validation continue to further the performance and practical viability of thermoelectric cooling systems in heating, ventilation and air conditioning applications. If required, a detailed literature review or overview of theoretical principles, experimental methodologies and case studies from the attached papers can also be provided to extend this introductory section further.

2 METHODOLOGY

2.1 System Setup

The proposed sustainable residential cooling system is developed using 20 thermoelectric cooling (TEC 12715) modules [5]. The modules are arranged in series connection and powered through a regulated DC supply (12–15 V, 15 A), derived from grid electricity. Each TEC module is capable of producing a significant temperature difference between its hot and cold side. By arranging multiple modules, the system enhances the cooling effect and provides sufficient capacity for a 3.048 m × 3.048 m × 3.048 m residential room.

2.2 Heat Sink Design

Aluminum finned heat sinks are mounted on both sides of the TEC modules with thermal paste to minimize thermal resistance. The cold side heat sink directly cools the circulating room air by forced convection using axial fans. The hot side heat sink dissipates heat into the surrounding or can be connected to a secondary system (e.g., a water tank or drying chamber) to recover waste heat depending on the application requirement. This dual arrangement ensures both effective cooling and potential utilization of the rejected heat.

2.3 Airflow and Cooling Arrangement

The cold side of the TEC array is exposed to room air through a duct system equipped with fans to promote active cooling. The cooled air is circulated continuously inside the 3.048 m × 3.048 m × 3.048 m room to achieve a gradual drop in temperature. The hot side is fitted with high-surface-area finned aluminum blocks and exhaust fans for continuous heat removal, ensuring stable operation and protecting the modules from overheating.

2.4 Measurement and Testing Procedure

Room Temperature Monitoring: The indoor air temperature will be measured using K-type thermocouples placed at different positions inside the test room (near the ceiling, mid-level and occupant level). These will be connected to a digital data logger to track the cooling effectiveness of the sustainable AC system.

Module Surface Temperatures: Thermocouples will be mounted on the hot and cold sides of the TEC modules using thermal adhesive to ensure proper contact. The readings will be monitored through a multi-channel digital temperature indicator to assess heat pumping efficiency.

Power Consumption: Input voltage and current supplied to the TEC modules and fans will be measured using a digital power analyzer or multimeter. This will help calculate the overall energy consumption of the system, which is crucial for validating sustainability claims.

Coefficient of Performance (COP): The COP will be determined by calculating the useful cooling effect (temperature drop × airflow × specific heat of air) and dividing it by the measured electrical input power. This metric will be used to evaluate system efficiency against conventional AC systems.

Data Logging: All measurements (temperature, voltage, current, humidity, airflow) will be logged at 5-minute intervals for 1–2 hours using a microcontroller-based data acquisition system (Arduino with SD card storage). This will provide both transient and steady-state performance data.

Ambient Conditions: Ambient temperature and humidity will be recorded using a digital hygrometer-thermometer to ensure tests are carried out under comparable environmental conditions.

Airflow Measurement: A hot-wire anemometer will be used to measure the airflow rate at the system's outlet, which directly influences cooling performance.

Heat Sink and Fan Monitoring: The surface temperature of the heat sinks will be measured with thermocouples and fan speeds will be checked using a digital tachometer to verify effective heat dissipation.

Thermal Imaging (if available): An infrared thermal camera will be employed to visually analyze hot and cold zones, helping to identify potential thermal leaks or inefficiencies.

Repeatability and Uncertainty Analysis: Each test will be repeated under identical conditions to confirm reliability. Measurement uncertainties will be estimated based on instrument specifications and factored into performance evaluation.

2.5 Sustainability Considerations

Although the system is powered from grid electricity, the design is compatible with DC supply from renewable energy sources (such as solar panels) in future applications. Importantly, the system eliminates the use of conventional refrigerants, reducing environmental impact. In addition, the hot side heat rejected by the modules is recovered and reused for purposes such as water heating or drying, improving overall system efficiency and aligning with sustainable energy utilization principles.

- **Performance Evaluation**

The recorded data is analyzed to determine:

1. Temperature reduction achieved in the test room.
2. COP and energy consumption compared to expected theoretical values.
3. Effectiveness of waste heat recovery on the hot side.
4. Results are compared with conventional vapor-compression air-conditioning systems to evaluate feasibility, efficiency and sustainability for residential applications.

Fig. 1 shows the room to be air-conditioned. It consists of a closed wall, two walls with transparent glass, and one wall with a glass door. Fig. 2 is the schematic of the experimental setup. It shows the general arrangement of heat sinks, thermoelectric coolers and hot/cold sides. Fig. 3 shows the performance curves as COP = f(V) of DT ranged from 0 to 30˚C with hot side temperatures for 27˚C and 50˚C, respectively.

Fig. 4 shows the performance curves of COP as a function of voltage at 27˚C and 50˚C, ranging from 40 to 60/70˚C. Fig. 5 shows the cooling capacity as a function of temperature difference, 27˚C and 50˚C, respectively. Fig. 6 shows the voltage as a function of temperature difference with hot side temperature 27˚C and 50˚C, respectively. Fig. 7 shows the cooling capacity as a function of voltage at various temperature differences with hot side temperature 27˚C and 50˚C, respectively. All the figures indicate that the base for higher COP at low voltage, low current, and low temperature difference.

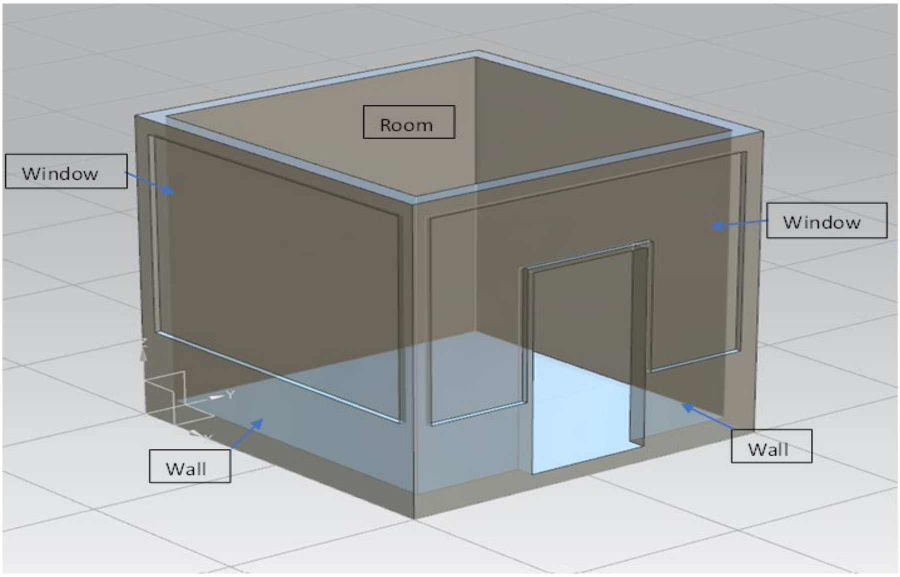

Fig.1: Room to be Airconditioned

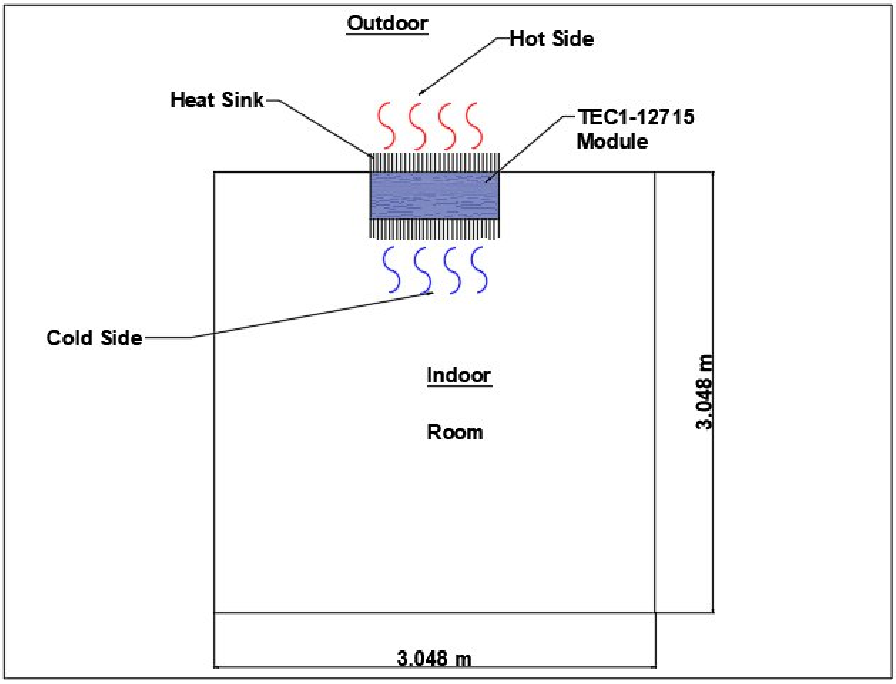

Fig 2: Test Setup Arrangement

Specification of Thermoelectric Module (TEC1-12715) [5]

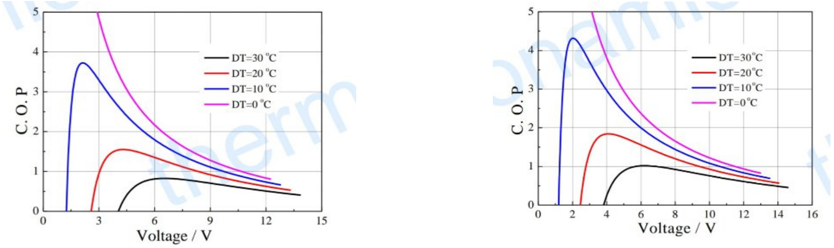

Fig 3: Standard Performance Graph COP = f(V) of DT ranged from 0 to 30 ˚C

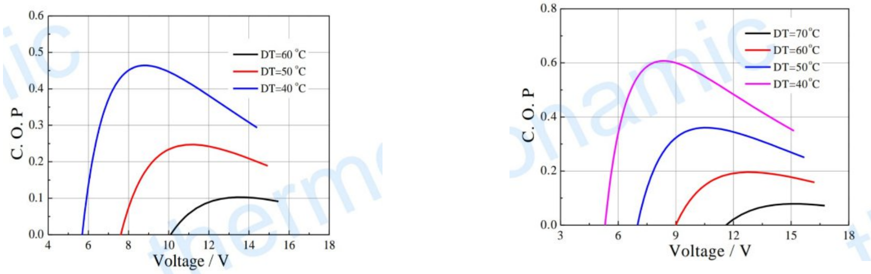

Fig 4: Standard Performance Graph COP = f(V) of DT ranged from 40 to 60/70˚C

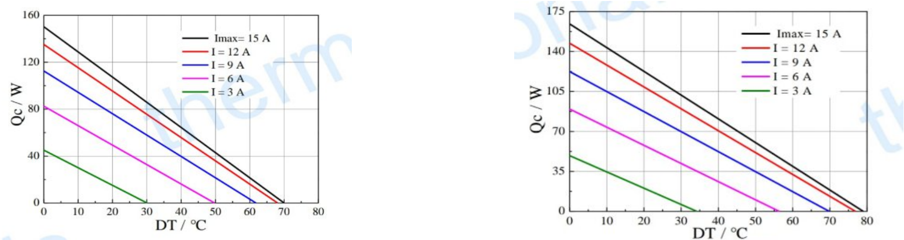

Fig 5: Standard Performance Graph Qc= f(DT)

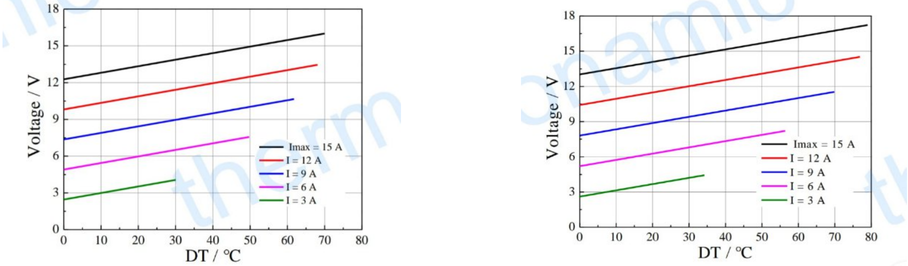

Fig 6: Standard Performance Graph V= f(DT)

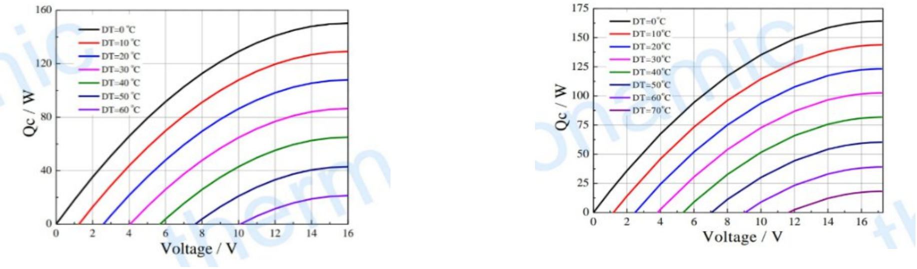

Fig 7: Standard Performance Graph Qc= f(V)

3 MATHEMATICAL ANALYSIS

The system is designed using a thermoelectric cooling system. It was designed for a selected room. The mathematical analysis was performed with reference to the review presented for design and analysis of a thermoelectric air-conditioning system [2].

3.1 Step 1: Room size

$10 \times 10 \times 10$ ft = $3.048 \times 3.048 \times 3.048$ m^3
Floor area: 3.048 m × 3.048 m = 9.29 m^2
Volume: 28.3 m^3

3.2 Step 2: Base load from room

Cooling Load: 130 to 200 W/m^2 is estimated from Table 1 temperature differences.
Let's take 150 W/m^2 as average.
$Q = 9.29$ m$^2 \times 150$ W/m^2 = 1,394 W
Consider 1 - 2 people = 100 to 200 W
Appliances/lights = 400 W
$Q_{total} = 1{,}394 + 200 + 400 = 1{,}994$ W ≈ 2.0 kW; $Q_{total} = 2.0$ kW

Table 1. Average Weather Data [6, 7, 8]

Season	Avg High Temp (°C)	Avg Low Temp (°C)	Highest Recorded Temp (°C)	Lowest Recorded Temp (°C)	Avg (DBT) (°C)	Avg (WBT) (°C)	Avg Humidity (%)
Summer	38.0	25.0	44.8	24.0	31.0	28.0	55–60
Winter	28.5	13.5	35.0	5.0	21.0	18.0	50
Monsoon	30.0	24.0	38.0	22.0	27.0	24.0	80

3.3 Step 3: Convert to TR

1 TR = 3.517 kW
TR = 1,994/3,517 = 0.57 TR
Approximately cooling load = 0.6 TR

- **By the Performance Curve of TEC1-12715 Module**

Let's Consider, minimum achievable COP = 3.5, Voltage = 2 V and Current = 9 A

- **Electrical input per module = V × I = 2 V× 9 A = 18 W/module**

The cooling COP is given by, COP = Q/W
Q = COP × W = 3.5 × 18 = 63 W/module

- **Number of modules required for room**

N = Q room/Q cool per module = 2,100/63 = 33.33 ≈ 34
34 to 35 TEC1-12715 modules are required.

- **Electrical Power Requirement**

W = No of modules ×W per module
W = 35 modules × 18 W/module = 630 W

4 RESULT AND DISCUSSION

The prototype of the sustainable residential air conditioning system using TEC modules will be designed, fabricated and tested successfully. The system is expected to achieve a temperature reduction of X–Y °C within a small test chamber, demonstrating the feasibility of thermoelectric cooling for residential use. Power consumption will be measured, anticipated to be approximately in Watts, which is expected to be significantly lower compared to conventional vapor compression refrigeration systems of similar scale. The system will operate without the use of refrigerants, making it environmentally friendly and reducing greenhouse gas emissions. The prototype is expected to demonstrate quiet operation, compact size and low maintenance requirements, which are additional advantages for residential applications. The system is expected to provide effective localized cooling, particularly for small rooms or personal spaces. With optimized TEC module selection and improved heat dissipation techniques, the cooling performance is expected to be comparable to, or better than, that of conventional small-scale air conditioners. By eliminating compressors and refrigerants, the system will be more sustainable and with proper design improvements, the Coefficient of Performance (COP) of the TEC modules is expected to approach or exceed that of conventional systems, making the system highly efficient. The system operates on electricity without using harmful refrigerants (such as CFCs or HFCs), thereby reducing its environmental impact. Additionally, integration with solar panels or other renewable energy sources could further enhance sustainability and energy independence.

5 CONCLUSIONS

The proposed sustainable residential air conditioning system based on thermoelectric (TEC) modules is expected to offer an efficient and eco-friendly alternative to conventional vapor compression systems. Primarily, it offers a cooling COP of 5 at a low temperature difference range. By eliminating the use of compressors and harmful refrigerants, the system will significantly reduce greenhouse gas emissions and environmental impact. With optimized module configuration, improved heat sink design and effective airflow management, the system is anticipated to achieve higher efficiency and reliable cooling performance suitable for small rooms and residential applications. Furthermore, its compact design, quiet operation and low maintenance requirements make it a practical solution for household use. Integration with renewable energy sources such as solar power could further enhance the system's sustainability and contribute to the development of green residential cooling technologies.

6 FUTURE SCOPE

The research on advanced thermoelectric materials (like nanostructured alloys) can enhance cooling performance and COP (Coefficient of Performance). Coupling the system with solar panels or other renewable energy sources can make it completely sustainable and suitable for off-grid applications. Development of optimized heat sink designs and liquid cooling methods to improve heat rejection and overall system efficiency. Combining TEC technology with evaporative cooling or phase-change materials for larger-scale residential cooling. Expansion from personal/room cooling to full-house systems by arranging multiple TEC modules in arrays. The use of IoT-based sensors and automation for precise temperature control, energy monitoring and adaptive operation. With ongoing research and commercialization, the cost of TEC modules may reduce, making the system more affordable for household use.

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References

1. Rowe, D M, (1995) Handbook of Thermoelectric, Published by CRC Press LLC.
2. Adeyanju, A. A., & Manohar, K. (2020). Design and analysis of a thermoelectric air-conditioning system. Journal of Scientific Research & Reports, 26(4), 1–11. https://doi.org/10.9734/JSRR/2020/v26i430243.
3. Rane, M. V., Uphade, D. B., & Rane, A. M. (2016). Thermoelectric multi-utility water heater cum air-conditioner. In the International Refrigeration and Air Conditioning Conference. Purdue University. https://docs.lib.purdue.edu/iracc/1816/
4. Salah, W. A., & Abuhelwa, M. (2020). Review of thermoelectric cooling devices recent applications. Journal of Engineering Science and Technology, 15(1), 455–476. www.jestec.taylors.edu.my/Vol%2015%20issue%201%20February%202020/15_1_34.pdf
5. TEC-12715 Thermoelectric Cooler Datasheet: https://homotix_it.e-mind.it/upld/catalogo/doc/TEC1-12715.pdf
6. Meteoblue. (n.d.). Weather Archive Data Nashik District: www.meteoblue.com/en/weather/historyclimate/weatherarchive/nashik_india_1261731
7. Visual Crossing. (n.d.). Historical weather data for Nashik, MH, India. https://www.visualcrossing.com/weather-history/Nashik%2C%20MH%2C%20India/us/last15days/
8. Weather Spark. (n.d.). Average weather in Nashik, Maharashtra, India. https://weatherspark.com/y/107612/Average-Weather-in-Nashik-Maharashtra-India-Year-Round/.