ENGR-UH 3110

Instrumentation, Sensors, Actuators

Multi-Stage TEC-based Compressor-Less Refrigerator

Project Report

Week 1 - Project Initiation, Research, and Planning

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Table of Contents

Introduction

The goal of this project is to design, prototype, and build a compact refrigerator using Thermoelectric Cooling (TEC1-12703, or TEC1-12706) modules in a stacked or parallel configuration. The system will be controlled by an Arduino board (either Uno or Due) and will integrate temperature sensors, an LCD interface, Rotary encoders, Power MOSFEts and appropriate power electronics (such as a buck converter and MOSFET drivers) to regulate the cooling. The final unit must be capable of maintaining a set temperature adjustable between 2°C and 12°C within a provided thermal enclosure (thermocol white box or a cold box for outdoor trips).

Literature Review

TEC Technology

What it is

Thermoelectric technology is an energy technology enabling power generation or cooling that involves the direct conversion of thermal energy into heat energy and vice versa via thermoelectric materials.

How it works

- Two distinct conducting materials, one with positive charge carriers (holes) and the other with negative charge carriers (electrons), combine to produce a junction in a typical thermoelectric device. Both kinds of charge carriers travel away from the junction and transfer heat away when an electric current is run through it in the proper direction, thus cooling the junction [3][1].
- TEC Modules

[1] DiSalvo, F. J. "Thermoelectric Cooling and Power Generation." *Science*, vol. 285, no. 5428, July 1999, pp. 703–6, https://doi.org/10.1126/science.285.5428.703.

Figure 1: TEC1-12703

TEC (Peltier) modules are devices of thermoelectric couples (N and P-type semiconductor pellets), electrically arranged (coupled in series) and thermally equal, that are inserted between ceramic plates. Generally, the material used for the semiconductor pellets are alloys of Bismuth Telluride (Bi_2Te_3). When a voltage is applied, current flow generates a temperature change. One side of the plate absorbs heat energy from one material surface and releases it to the other side [6].[2]

Advantages of TEC modules for refrigeration

- Lightweight
- Small and compact
- Inexpensive
- Eliminates the need for liquids or gases to pump heat from cold to hot
- Less prone to failure because there are no mechanical moving parts
- Can be powered by direct current (DC) electric sources

Disadvantages of TEC devices for refrigeration

- Low efficiency
- Temperature Control Limitation

[2] K. Shilpa, M., et al. "A Systematic Review of Thermoelectric Peltier Devices: Applications and Limitations." *Fluid Dynamics & Materials Processing,* vol. 19, no. 1, 2023, pp. 187–206, https://doi.org/10.32604/fdmp.2022.020351

Thermodynamic Fundamentals

First Law of Thermodynamics

Conservation of energy: electrical energy is converted into heat transfer in thermoelectric cooling

Second Law of Thermodynamics

Heat flows from hot to cold naturally; therefore, thermoelectric devices require work to reverse this flow.

Peltier Effect

If a current is passed through a junction between two dissimilar conductors there is either a heating or cooling effect at the junction. This is known as the Peltier effect and its magnitude is given by the relation:

$$Q = \pi I$$

where Q is the rate of heat release or absorption, I is the current, and π is the Peltier coefficient. Peltier coefficients range from 3 V for metals, 30 V for highly doped semiconductors to 300 V for lightly doped semiconductors.[3]

Efficiency

- The **coefficient of performance (COP)** is used to express the efficiency of a refrigerator. It is the amount of cooling divided by the electrical energy input needed to obtain that cooling. According to the laws of thermodynamics, a maximum efficiency – the **Carnot efficiency** – cannot be exceeded. The COP at Carnot efficiency is $T_{cold}/(T_{hot}-T_{cold})$, where T_{hot} refers to the temperature of the ambient environment and T_{cold} is the temperature of the coldest part of the refrigerator. The real efficiency of any device is often given as a percentage of the Carnot efficiency. “Present TE devices operate at about 10% of Carnot efficiency, whereas the efficiency of a compressor-based refrigerator increases with size:

[3] Dryden, I. G. C., editor. The Efficient Use of Energy. 2nd ed., Butterworth-Heinemann, 1982, www.sciencedirect.com/book/9780408012508/the-efficient-use-of-energy#book-info.

a kitchen refrigerator operates at about 30% of Carnot efficiency and the largest air conditioners for big buildings operate near 90%”.[4]

- Efficiency of TEC devices is determined by materials used in making the device.

Key Performance Targets

Setpoint Temperature Range[5]

The refrigerator must be capable of maintaining an adjustable temperature between **2°C and 12°C**. This temperature range is commonly required for products such as vaccines, laboratory samples, and perishable goods. Maintaining precise and adjustable temperature control is crucial for ensuring product integrity.

- This range (2°C - 12°C) is suitable for preserving perishable items and aligns with typical refrigeration requirements.

Cooling Power[6] [7]

Thermoelectric systems (Peltier-based) generally offer cooling capacities in the lower range, typically in the range to around 100W. These systems are well-suited for applications requiring precise temperature control, but their cooling capacity is limited compared to compressor-based systems. Peltier systems excel in small, compact refrigeration units, such as those used for personal or small-scale scientific applications (Source: LabIncubators).

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4 DiSalvo, F. J. “Thermoelectric Cooling and Power Generation.” *Science*, vol. 285, no. 5428, July 1999, pp. 703–6, https://doi.org/10.1126/science.285.5428.703.
5 Ashour, Ali M., et al. “Experimental Analysis of the Temperature Distribution inside Vaccine Freezer Compartment Based on Hybrid Refrigeration System.” *Energy Conversion and Management*, vol. 300, Pergamon, Dec. 2023, p. 117967, https://doi.org/10.1016/j.enconman.2023.117967.
6 Ashour, Ali M., et al. “Experimental Analysis of the Temperature Distribution inside Vaccine Freezer Compartment Based on Hybrid Refrigeration System.” *Energy Conversion and Management*, vol. 300, Pergamon, Dec. 2023, p. 117967, https://doi.org/10.1016/j.enconman.2023.117967.
7 “Peltier vs. Compressor-Based Cooling | Blog | LabIncubators.net.” *Labincubators.net*, labincubators.net/blogs/blog/peltier-vs-compressor-based-cooling.

The efficiency of Peltier systems tends to decrease as the temperature differential increases. For example, when the internal temperature is set to be significantly cooler than the ambient temperature, the system needs more energy to maintain this difference. This results in less energy efficiency for larger applications

Response Time[8] [9]

Thermoelectric systems offer very fast response times because they adjust the cooling effect almost instantly. This is due to the nature of Peltier elements, which can change their cooling output directly with the adjustment of electrical current. The system's heat transfer is almost immediate, meaning rapid cooling or heating responses when the temperature deviates from the setpoint.

With better dynamic response times, Peltier systems are ideal in environments where temperature fluctuations must be minimized, such as laboratory settings requiring a constant and highly stable temperature.

Thermal Efficiency and Power Consumption[10]

Thermoelectric systems generally have lower thermal efficiency than compressor-based systems, with a coefficient of performance (COP) often less than 1. This makes them less power-efficient for large-scale cooling applications. The energy consumption of Peltier-based systems increases significantly as the desired temperature differential grows, making them less suitable for high-performance applications requiring efficient power usage.

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[8] Zhou, Lin, et al. "Multi-Stage Thermoelectric Coolers Current Optimization for Infrared Detectors Based on the SNOPT-Finite Element Method." *Applied Thermal Engineering*, vol. 252, Pergamon, May 2024, p. 123498, https://doi.org/10.1016/j.applthermaleng.2024.123498.

[9] Feng, Jianghe, et al. "Low-Temperature Thermoelectric Materials and Applications." *Nano Energy*, vol. 126, Elsevier, Apr. 2024, p. 109651, https://doi.org/10.1016/j.nanoen.2024.109651.

[10] "Electronic Enclosure Cooling Thermoelectric vs. Compressor-Based Air Conditioners | the World Leader in Thermal Management Solutions." *Lairdthermal.com*, lairdthermal.com/thermal-technical-library/white-papers/electronic-enclosure-cooling-thermoelectric-vs-compressor-based-air.

User Interface and Control System[11] [12]

The user interface for controlling the refrigeration system is an essential feature, ensuring ease of use for adjusting the temperature settings and monitoring performance. Modern refrigeration units often use digital control systems with temperature sensors and microcontrollers to maintain precise temperature settings. These systems should include user-friendly interfaces with screens and dials.

For thermoelectric systems, the interface may allow users to control the current supplied to the Peltier element, whereas compressor-based systems will typically include thermostat settings for regulating compressor cycling. In both cases, effective feedback from temperature sensors ensures that the system maintains the desired temperature range accurately.

Thermoelectric Module Configurations

TE devices are composed of thermoelectric couples (N and P types) that are connected either in electrically series (stacking) or in parallel thermally. They are fixed by coldering, sandwiched between two ceramic plates. The latter form the hot and cold thermoelectric cooler sides.

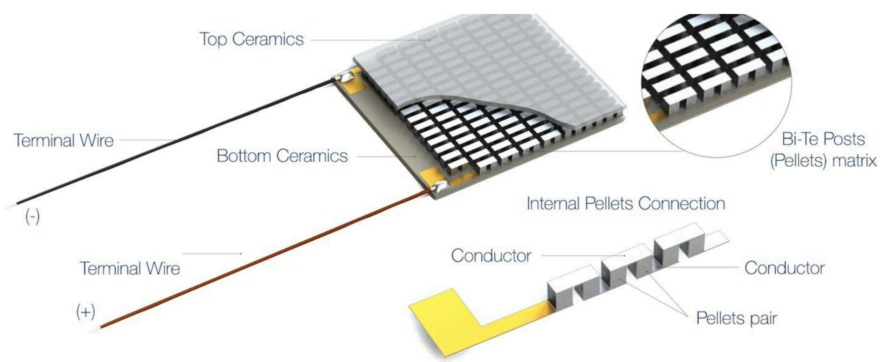

Figure 2: Single Stage TEC with two ceramic plates[13]

[11] Zhou, Lin, et al. "Multi-Stage Thermoelectric Coolers Current Optimization for Infrared Detectors Based on the SNOPT-Finite Element Method." *Applied Thermal Engineering*, vol. 252, Pergamon, May 2024, p. 123498, https://doi.org/10.1016/j.applthermaleng.2024.123498.
[12] Liu, Ziwen, et al. "Design and Optimization of a Cubic Two-Stage Thermoelectric Cooler for Thermal Performance Enhancement." *Energy Conversion and Management*, vol. 271, Elsevier BV, Oct. 2022, pp. 116259–59, https://doi.org/10.1016/j.enconman.2022.116259.
[13] "Thermoelectric Coolers Introduction - the Basics." *TEC Microsystems*, https://www.tec-microsystems.com/faq/thermoelectic-coolers-intro.html.

Commonly a TE module consists of a regular matrix of TE elements, ceramic plates, electric conductors and solders. A single-stage module consists of one matrix of pellets and a pair of cold and warm sides. It typically produces a maximal temperature difference of 70 °C between its hot and cold sides. The more heat moved using a TEC, the less efficient it becomes, because the TEC needs to dissipate both the heat being moved and the heat it generates itself from its own power consumption.

A multi-stage module can be viewed as two or more single stages stacked on top of each other. The construction of a multi-stage module is usually of a pyramidal type, each lower stage is bigger than the upper stage. Multistage modules are highly required when the temperature difference is large.[14]

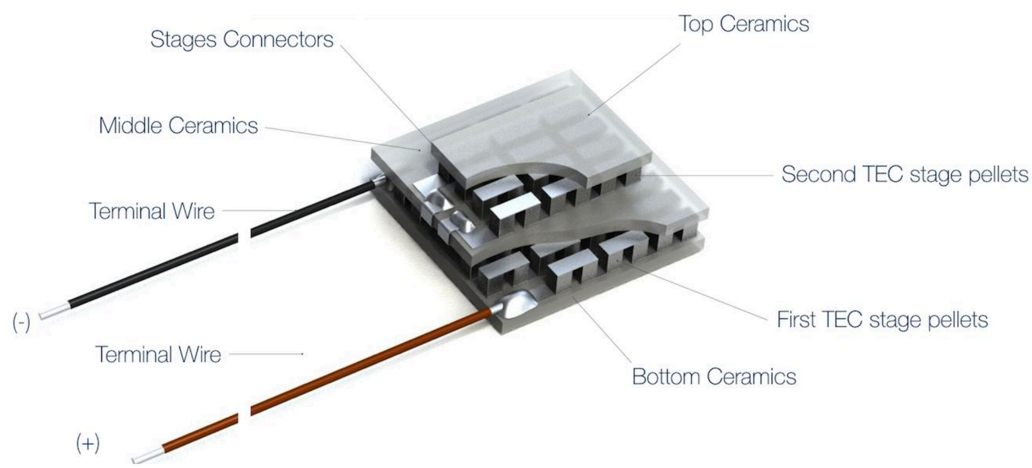

Figure 3: Multi Stage TEC[15]

TEC modules can achieve a larger temperature difference ΔT by staking stages, however , each additional stage must also pump the heat from the previous stage, greatly increasing the heat load on the final module. In contrast, using TECs in parallel can increase overall cooling capacity, but electrically wiring modules in parallel is challenging due to current sharing issues. Table 1, provides a more detailed comparison of the two configurations. In practice, parallel

[14] Cooling Performance of Thermoelectric Cooling (TEC) and Applications: A review." *MATEC Web of Conferences*,
[15] "Thermoelectric Coolers Introduction - the Basics." *TEC Microsystems*,

TECs often need to be driven individually to ensure each module shares the cooling load properly.[16]

Feature	Stacking Configuration	Parallel Configuration
Temperature Gradient	Higher	Lower , better stability
Cooling Capacity	Lower capacity per stage	Higher capacity per unit
Power Consumption	Higher due to multiple TECs in series	More efficient per cooling watt
Heat Dissipation Needs	Moderate	High, requires efficient dissipation
Application Suitability	Low-temperature applications	General cooling solutions

Table 1: Comparison of TEC stacking vs parallel configurations.

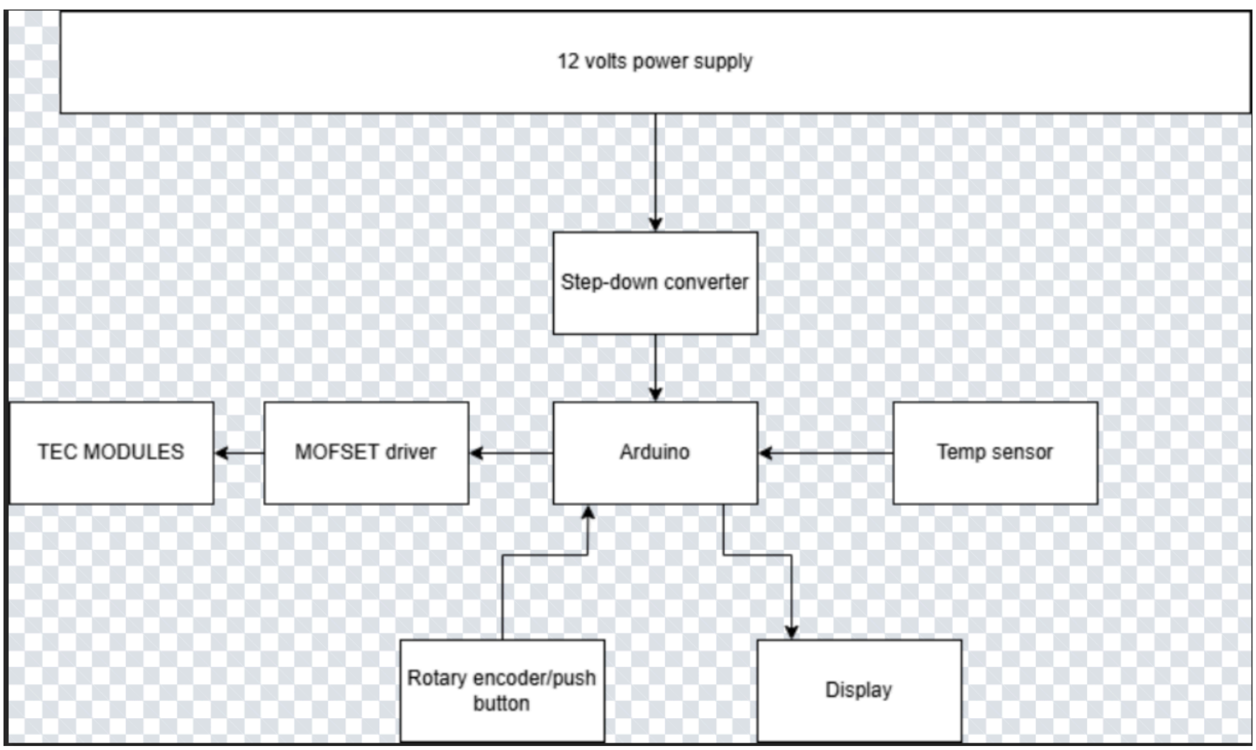

Figure 4: Block diagram of components

[16] Westby, Robert. “What to Do for Higher Power Thermoelectric Cooling Using a Peltier Device.” *Analog Devices*, 17 November 2024

Case Studies

Similar projects and case studies of Peltier-based refrigerator projects are as follows:

1. *Beer Fridge: A Case Study in Thermal Design - Part 2: TEC Effect* [17]

This study explores the thermal challenges of using TECs in refrigeration. It examines the impact of heat sink selection, airflow management, and insulation on TEC efficiency. The study highlights how TEC stacking improves temperature differentials, enhancing cooling performance. Power supply optimization is also discussed to maximize energy efficiency.

2. *Experimental Studies on Thermoelectric Refrigeration System* [18]

This study investigates the performance of thermoelectric refrigeration systems using Peltier modules. It explores how factors such as heat sink design, insulation, and power supply influence cooling efficiency. Experimental results demonstrate the potential of TEC-based refrigeration in low-power applications.

3. *A Thermoelectric Refrigerator Using Arduino* [19]

This study presents the design and implementation of an Arduino-based thermoelectric refrigerator using TEC modules. It explores the energy efficiency, temperature control, and feasibility of TECs for refrigeration applications. The system incorporates temperature sensors, a microcontroller, and a cooling mechanism to regulate internal conditions. Experimental results highlight the effectiveness of TECs for small-scale cooling with minimal energy consumption.

4. *Thermoelectric Portable Mini-Fridge Using Arduino* [20]

[17] "Beer Fridge: A Case Study in Thermal Design - Part 2: TEC Effect." Electronics Cooling, 1 Dec. 2010
[18] Sahu, M. K., et al. "Experimental Studies on Thermoelectric Refrigeration System." *ResearchGate*, Apr. 2019
[19] Shree, K.K. Shandhosh, et al. *"A Thermoelectric Refrigerator Using Arduino." Middle East Journal of Applied Science & Technology (MEJAST)*, vol. 6, no. 2, 2023, pp. 1-10.
[20] Alam, M. K., et al. *"Thermoelectric Portable Mini-Fridge Using Arduino." AIP Conference Proceedings*, vol. 2129, no. 1, 2019, pp. 020145. American Institute of Physics, DOI: https://doi.org/10.1063/1.5118033.

This paper presents the design and testing of a thermoelectric portable mini-fridge controlled by Arduino. The system utilizes Peltier modules (TECs) for solid-state cooling, integrating temperature sensors for precise control. Experimental results show the effectiveness of PID control in maintaining stable cooling performance. The study evaluates energy consumption, cooling efficiency, and real-world applications. Findings suggest TEC-based fridges are feasible for portable use but require optimized heat dissipation for improved efficiency.

5. *Homemade Peltier Cooler with Temperature Control - DIY* [21]

This DIY guide demonstrates how to build a Peltier-based thermoelectric cooler with temperature control. The project uses a TEC module, heat sinks, a temperature sensor, and a microcontroller to regulate cooling. The tutorial explains wiring, power management, and efficiency considerations for stable operation. Users can modify the system for portable refrigeration, electronics cooling, or custom temperature-controlled enclosures. The guide emphasizes proper heat dissipation and insulation to enhance TEC performance.

Condensation Management

Water vapor in the air will condense into liquid on any surface cooled below the air's dew point, which in a TEC refrigerator means the cold-side heatsink. If not managed, this condensate can pool inside the enclosure, leading to mold growth and reduced performance. This is damaging to health and performance parameters.[22]

The most effective strategy is to collect the condensation and remove it from the cooled compartment before it re-evaporates. In practice, this means designing a drainage path.

I.e a drip tray or channel beneath the cold-side radiator that funnels water out of the refrigerated space

[21] Instructables. *"Homemade Peltier Cooler w/ Temperature Control - DIY." Instructables*, 2023

[22] *LabFreezers.net. "labfreezers.net." LabFreezers.net, n.d.,* https://labfreezers.net.

Gravity can carry the water to an external reservoir or drip pan where it can safely evaporate. An internal fan can be used to circulate air over the cold radiator, encouraging moisture to condense on the fins and then drain away. Passive solutions like this require minimal complexity: one could simply include a small drain hole at the lowest point of the cold chamber leading to a container or an absorbent pad outside.[23]

Active removal methods can also be integrated for efficiency: for instance, a tiny condensate pump or an absorbent wick could draw water to the outside if gravity draining is difficult. Another approach is to use a heated evaporation tray outside the cold chamber – a small electrically heated basin where the drain line terminates to vaporize the collected water.

Condensation and Frost Mitigation Strategies

Ice has a much lower thermal conductivity than metal and also adds an insulating barrier between the cold surface and the air. In the early stages a thin frost layer might slightly increase surface area, but very quickly it impedes conductive heat flow, causing a drop in cooling efficiency. This causes the TEC has to work harder to pull heat through the frost, and the interior may no longer reach its target low temperature. To maintain performance, the design must prevent excessive ice accumulation or periodically remove it.

One basic preventive strategy is to minimize how often the cold surfaces go far below 0 °C: for example, if the thermostat set-point is just above freezing (say 2–5 °C), the TEC should be controlled so that it doesn't supercool the radiator much colder than needed. This can reduce the rate of frost formation. However, in practice even at 2 °C interior, the TEC's cold plate might dip below freezing to achieve that, so frost is still likely.

Active de-icing mechanisms are commonly required in refrigeration systems. A traditional approach is to implement a defrost cycle: temporarily warming the cold-side to melt accumulated

[23] *Koolatron. "koolatron.com." Koolatron, n.d.,* https://koolatron.com.

ice, then draining the water away. In a TEC system, this could be done by reversing the current to turn the cold-side into a heater for a short interval.[24]

Another method is an "off-cycle" defrost. Turning off the cooling periodically, allowing the cold side to warm up from the ambient or from the insulated cabinet's air, thus melting frost naturally. This can be scheduled or triggered by sensors. A sensor-based de-icing control might use a temperature sensor on the cold heatsink or a humidity/frost sensor to detect when frost is forming.

> I.e If the cold-side surface remains at 0 °C or below for an extended time or if airflow through the radiator diminishes, the controller could pause cooling or activate a heater until the sensor indicates the ice has melted.

Thermodynamically, melting the ice requires input of heat (the latent heat of fusion); this introduces an energy penalty, but it restores efficient heat exchange by removing the insulating frost, ultimately maintaining overall system performance.

Design-wise, the radiator and enclosure should be configured to handle these defrost events: the melted ice must be drained or absorbed just like regular condensate, and materials should withstand the thermal cycling. Additionally, to mitigate ice buildup in the first place, one can reduce ambient moisture ingress (a tight door seal and minimal door openings will keep humidity low) and possibly use fins or coatings that resist frost adherence.

> I.e hydrophobic or antifreeze coatings on the cold-side fins can delay frost onset by making it harder for ice to stick.[25] [26]

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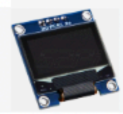
[24]*RXinsider. "rxinsider.com." RXinsider, n.d., https://rxinsider.com.*

[25]*EIC Solutions. "info.eicsolutions.com." EIC Solutions, n.d., https://info.eicsolutions.com.*
[26]*RXinsider. "rxinsider.com." RXinsider, n.d., https://rxinsider.com.*

Hardware

(link to inventory)

Inventory_tracker1

Item ID	Item name	Stock	Item Holder	Category	Notes	Image
TEC1-12703	Thermoelectric Cooler (TEC) Module	##		Electronics...	transfers heat using the Peltier effect. useful for precise temperature control in cooling applications like mini-fridges or electronic cooling.	
Arduino UNO R3	Arduino Board	2	Ahmed ...	Electronics...	microcontroller board (ATmega328P) useful for interfacing with sensors and actuators	
2C11 Rotary Encoder Module Brick Sensor KY-040	Rotary Encoder	1	Ahmed ...	Electronics...	useful for motor speed regulation	
2D2 IRF520 MOSFET Driver Module	MOS Module	2	Ahmed ...	Electronics...	switches high-power loads with low-power signals using MOSFET. useful for controlling motors, LEDs, and other high-current components with a microcontroller.	
DS18B20	Digital Temperature Sensor Probe	2	Hiba As...	Electronics...	useful for precise temperature measurement in various environments, including liquids.	
52Pi I2C 0.96 inch OLED display, 128x64px, 2-color screen	0.96 inch OLED display	2	Ahmed ...	Electronics...	useful for displaying sensor readings, menus, or system status in compact electronic projects.	
Item ID	Male to Female Wires	40	Ahmed ...	Electronics...	useful for prototyping with breadboards and microcontrollers.	
LM2596 adjustable buck converter	Buck Converter	##		Power	useful for providing a stable lower voltage to circuits from a higher power source. IC on it called LM2596 is a power converter regulator	
Item ID	Aluminium Heat Sink	##	Ahmed ...	Cooling an...	passive cooling component that dissipates heat from electronic components useful for preventing overheating in power electronics and microprocessors.	
ICE400SE, 4 heat pipes, aigo	CPU cooler fan	1	Ahmed ...	Cooling an...	CPU cooling fan with heat pipes that enhances heat dissipation. useful for cooling high-power processors or similar heat-generating components.	
Hi Stick Polyurethane PU Insulating Foam Sealant, 750ml	PU Insulating Foam	1	Ahmed ...	Cooling an...	expands and hardens to seal gaps and provide insulation. useful for supplementary thermal insulation.	
Cosmoplast 24-L insulating icebox (Polyurethane PU insulation)	Cooler Box	1	Ahmed ...	Cooling an...	Product Weight: 2.7 kg Capacity: 24 Liters Product Dimensions: 41.5 x 28 x 35 cm Material: Plastic with PU Insulation	

References

[1] Alam, M. K., et al. *"Thermoelectric Portable Mini-Fridge Using Arduino." AIP Conference Proceedings*, vol. 2129, no. 1, 2019, pp. 020145. American Institute of Physics, DOI: https://doi.org/10.1063/1.5118033.

[2] "Beer Fridge: A Case Study in Thermal Design - Part 2: TEC Effect." *Electronics Cooling*, 1 Dec. 2010, https://www.electronics-cooling.com/2010/12/beer-fridge-a-case-study-in-thermal-design-part-2-tec-effect/.

[3] DiSalvo, F. J. "Thermoelectric Cooling and Power Generation." *Science*, vol. 285, no. 5428, July 1999, pp. 703–6, https://doi.org/10.1126/science.285.5428.703.

[4] Dryden, I. G. C., editor. The Efficient Use of Energy. 2nd ed., Butterworth-Heinemann, 1982, www.sciencedirect.com/book/9780408012508/the-efficient-use-of-energy#book-info.

[5] Instructables. *"Homemade Peltier Cooler w/ Temperature Control - DIY." Instructables*, 2023, https://www.instructables.com/Homemade-Peltier-Cooler-W-Temperature-Control-DIY-/

[6] K. Shilpa, M., et al. "A Systematic Review of Thermoelectric Peltier Devices: Applications and Limitations." *Fluid Dynamics & Materials Processing,* vol. 19, no. 1, 2023, pp. 187–206, https://doi.org/10.32604/fdmp.2022.020351.

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https://www.matec-conferences.org/articles/matecconf/pdf/2018/84/matecconf_ses2018_03021.pdf.

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[12] EIC Solutions. "info.eicsolutions.com." *EIC Solutions*, n.d., https://info.eicsolutions.com.

[13] RXinsider. "rxinsider.com." *RXinsider*, n.d., https://rxinsider.com.

[14] LabFreezers.net. "labfreezers.net." *LabFreezers.net*, n.d., https://labfreezers.net.

[15] Koolatron. "koolatron.com." *Koolatron*, n.d., https://koolatron.com.

[16] Ashour, Ali M., et al. "Experimental Analysis of the Temperature Distribution inside Vaccine Freezer Compartment Based on Hybrid Refrigeration System." *Energy Conversion and Management*, vol. 300, Pergamon, Dec. 2023, p. 117967, https://doi.org/10.1016/j.enconman.2023.117967.

[17] "Electronic Enclosure Cooling Thermoelectric vs. Compressor-Based Air Conditioners | the World Leader in Thermal Management Solutions." *Lairdthermal.com*, lairdthermal.com/thermal-technical-library/white-papers/electronic-enclosure-cooling-thermoelectric-vs-compressor-based-air.

[18] Feng, Jianghe, et al. "Low-Temperature Thermoelectric Materials and Applications." *Nano Energy*, vol. 126, Elsevier, Apr. 2024, p. 109651, https://doi.org/10.1016/j.nanoen.2024.109651.

[19] Liu, Ziwen, et al. "Design and Optimization of a Cubic Two-Stage Thermoelectric Cooler for Thermal Performance Enhancement." *Energy Conversion and Management*, vol. 271, Elsevier BV, Oct. 2022, pp. 116259–59, https://doi.org/10.1016/j.enconman.2022.116259.

[20] “Peltier vs. Compressor-Based Cooling | Blog | LabIncubators.net.” *Labincubators.net*, labincubators.net/blogs/blog/peltier-vs-compressor-based-cooling.

[21] Zhou, Lin, et al. “Multi-Stage Thermoelectric Coolers Current Optimization for Infrared Detectors Based on the SNOPT-Finite Element Method.” *Applied Thermal Engineering*, vol. 252, Pergamon, May 2024, p. 123498, https://doi.org/10.1016/j.applthermaleng.2024.123498.