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Evaluation of Smart Portable Cooling System for Temperature-Sensitive Medicine Delivery in Remote Regions of the Navajo Nation

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Abstract - **During the COVID-19 pandemic, delivering healthcare to remote and underserved populations became a pressing global issue. One of the most affected groups in the United States was the Navajo Nation, whose residents faced extreme difficulty accessing life-saving medications due to a combination of limited infrastructure, impassable roads, and lack of electricity. In response to these challenges, this study explores the development of a drone-based medicine delivery system featuring an integrated thermoelectric cooling unit to preserve pharmaceuticals at WHO-recommended temperatures (2°C to 8°C). Utilizing the Peltier effect through a thermoelectric module, the prototype maintains the required temperature range using a Styrofoam-based insulated container, reflective insulating adhesives, and a 12V automatic temperature controller. Several configurations of thermoelectric devices were tested both internally and externally to optimize performance. The system is a step toward providing autonomous, reliable cold-chain delivery to rural communities, mitigating risks associated with road inaccessibility and lack of refrigeration. Although the results are promising, further research is needed to reduce the cooling latency and improve energy efficiency. This work contributes to bridging the gap in healthcare accessibility and supports future implementations of drone-based medical logistics.**

Keywords - Thermoelectric Cooling, Peltier Effect, Drone Delivery, Cold Chain, Insulation, Indigenous Healthcare, Remote

1. INTRODUCTION

The COVID-19 pandemic exposed significant vulnerabilities in healthcare infrastructure across rural America, particularly within the Navajo Nation—a region already facing systemic barriers to medical access. With approximately 30% of homes lacking electricity and 40% without running water [1], the logistics of storing and transporting temperature-sensitive medications such as insulin and vaccines became an urgent concern. This crisis was exacerbated by poorly maintained roads, vast geographical isolation, and strained healthcare systems, leading to a disproportionate mortality rate among Navajo communities [2].

To address these disparities, this research explores the design and application of a drone-based portable cooling system for delivering essential medicines to remote locations. Drone delivery systems have gained momentum globally for their potential in healthcare logistics, especially in low-infrastructure environments [3], [4]. Companies like Zipline have demonstrated successful vaccine and blood deliveries using autonomous aircraft in regions like Rwanda and Ghana, paving the way for similar solutions in the U.S. [5]. In such systems, maintaining the pharmaceutical cold chain is critical. Failure to meet required storage temperatures can compromise the efficacy and safety of medications [6].

This paper focuses on the construction and testing of a cost-effective, portable thermoelectric cooling unit designed for drone delivery. The system leverages the Peltier effect—a principle in which heat is transferred between junctions of different semiconductors upon application of a direct current—to regulate temperature within a Styrofoam container [7], [8]. The cooling chamber is insulated with reflective adhesive materials and integrated with a temperature controller capable of automatic thermal regulation between 2°C and 8°C, in compliance with WHO guidelines for medicine storage [9].

Advanced insulation materials such as expanded polystyrene (Styrofoam) provide an effective barrier against heat due to their low thermal conductivity and closed-cell structure [10]. Additionally, phase change materials (PCMs) and reflective barriers are increasingly used to stabilize internal temperatures during transport [11], [12]. Thermoelectric modules, particularly those utilizing bismuth telluride (Bi_2Te_3), offer compact and solid-state cooling solutions suitable for unmanned aerial vehicles (UAVs) [13]. This paper contributes to the growing body of research on cold chain logistics in underserved communities, proposing a modular, affordable, and energy-efficient solution that combines thermoelectric technology with autonomous drone delivery. Future applications may include vaccine distribution, emergency medical supply deployment, and mobile diagnostics—enhancing healthcare equity for Indigenous and remote populations.

2. STYROFOAM CONTAINER

Maintaining a stable temperature environment is critical in the transportation of temperature-sensitive medical supplies, especially in remote regions. For this experiment, small Styrofoam coolers (as shown in Fig 1) were selected due to their availability, lightweight structure, and excellent insulation characteristics.

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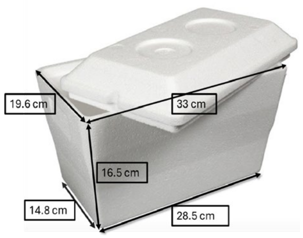

Fig 1. Small Styrofoam Container

Styrofoam shown in Fig 1, scientifically known as expanded polystyrene (EPS), is widely used in cold-chain logistics due to its low thermal conductivity, which minimizes heat transfer between the interior and exterior environments [10]. Its closed-cell structure traps air pockets, creating an effective barrier against conduction and convection, thus helping maintain a constant internal temperature for extended durations [14].

In the medical and pharmaceutical industry, EPS containers are commonly employed for the transportation of vaccines, biological specimens, and medications that require temperature control [15]. The cooler's performance in this context was enhanced using internal reflective insulation adhesives, which further reduce radiant heat transfer. The coolers used in this study were chosen based on volume, thermal insulation rating, and ease of integration with the cooling hardware.

The experimental configuration included:

A 12V thermoelectric Peltier module for active cooling

A digital temperature control switch with a sensor to monitor and regulate internal conditions

A battery pack serving as the power source

Heat sinks and fans attached to the hot side of the Peltier module to dissipate excess heat

Thermocouples placed at multiple points to monitor temperature variations

This setup allowed for controlled experiments to determine the effectiveness of thermoelectric cooling in maintaining the target temperature range of 2°C to 8°C, in alignment with WHO recommendations for medicine storage [16].

The system was evaluated in ambient conditions similar to those found in rural desert environments, such as those within the Navajo Nation, to simulate real-world applications. The performance was assessed based on the time required to reach target temperatures and the duration the temperature could be maintained without external intervention.

3. INSULATION MODEL DESIGN AND COOLING SYSTEM

3.1. Model 1 – Foam and Thermal Insulation Shield


Fig 2. Foam and Thermal Insulation Shield

Fig 2 shows a foam and Thermal Insulation. Foam is a widely utilized material due to its distinctive structure and insulation properties. It consists of numerous gas-filled cells encapsulated within a solid matrix, yielding a low-density, porous composition. This structure makes foam highly compressible, adaptable to various geometries, and an excellent thermal insulator [17]. Due to its shock-absorbing and cushioning capabilities, foam is commonly employed across construction, automotive, and packaging industries.

Thermal insulation shields are engineered to limit the transfer of heat between distinct environments. These shields typically consist of alternating layers of reflective metallic materials—such as aluminum foil—interleaved with insulating media like foam or fiberglass [18]. The reflective surfaces deflect radiant energy, while the insulating layers obstruct conductive and convective heat transfer. Their lightweight nature, combined with ease of installation and flexibility, makes them especially suitable for building envelopes, vehicle heat shields, and protective gear.

In this model, foam is strategically positioned on the inner surface of the Styrofoam chamber to provide immediate insulation around the contents. In parallel, thermal insulation layers are applied to both inner and outer surfaces of the Styrofoam container, enhancing overall thermal resistance and minimizing heat ingress from the external environment.

3.2 Model 2 – Reflective Foam and Double Reflective Insulation


Fig 3. Reflective Foam and Double Reflective Insulation

Reflective foam integrates traditional foam with metallic reflective films, typically aluminum-based, to improve thermal performance as shown in Fig 3. These reflective coatings repel incoming radiant heat, effectively decreasing the thermal load and increasing energy efficiency. Reflective foam is valued for its lightweight, moisture-resistant, and thermally resilient characteristics, rendering it an ideal choice for thermally regulated enclosures in construction and transportation applications [19].

Double reflective insulation enhances this concept further by embedding two layers of reflective foil on either side of a central insulating core, typically foam or fiberglass. This configuration combats all three modes of heat transfer: radiation, conduction, and convection. The presence of dual reflective barriers enhances temperature stability within the system, particularly under intense solar exposure.

In this model, the inner layer of the Styrofoam container is first lined with reflective foam, followed by a double reflective insulation layer. The exterior surface of the container is also covered with double reflective insulation alone, optimizing heat rejection while preserving the internal environment.

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3.3 Model 3 – Aluminum Foil

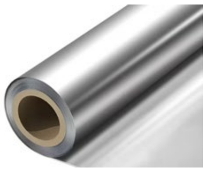

Fig 4. Aluminum Foil

Aluminum foil is a thin shown in Fig 4, highly reflective material with excellent thermal management properties. Fabricated through the rolling of pure aluminum into sheets as thin as 0.006 mm, aluminum foil can reflect up to 98% of infrared radiation [20]. It is also impermeable to gases, moisture, and light, making it ideal for environments where chemical and atmospheric isolation is critical.

In this configuration, aluminum foil is applied to both the inner and outer surfaces of the Styrofoam enclosure. This dual-layer approach creates a thermal envelope that significantly reduces radiant heat penetration, while also protecting against moisture ingress and microbial contamination—crucial when transporting temperature-sensitive pharmaceuticals.

4. THERMOELECTRIC COOLING SYSTEM

To actively control the internal temperature of the container, a Peltier module is integrated into the system as shown in Fig 5.

Fig 5. Peltier Device

The Peltier device, or thermoelectric cooler, operates on the Peltier effect, which involves the absorption or emission of heat at the junction of two dissimilar semiconductors—typically n-type and p-type materials—when an electric current is applied. These semiconductors are arranged in pairs and electrically connected in series, while thermally connected in parallel between two ceramic plates, as illustrated in Fig 6.

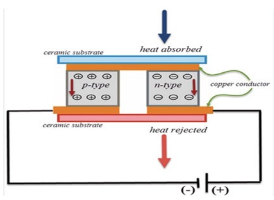

Fig 6. Electric Current Flow of N-Type and P-Type Semiconductor within Peltier Device

Upon applying a direct current, electrons move from the n-type to the p-type semiconductor, causing one side of the device to absorb heat (cooling effect), while the opposite side releases heat (heating effect)[21]. This thermodynamic process is reversible, allowing the device to alternate between heating and cooling modes simply by switching current direction [22].

The module is paired with a temperature sensor, such as an NTC thermistor, placed inside the container to monitor the internal conditions. A microcontroller-based control board receives this sensor data and adjusts power delivery to the Peltier module to maintain a precise temperature window—typically between 2°C and 8°C, suitable for medical cold-chain requirements [23].

E. Thermoelectric Cooling, Sensing, and Control Mechanism

Thermoelectric cooling relies on the Peltier effect, a phenomenon where heat is absorbed or released at the junction between two different semiconductors when an electric current passes through them. Specifically, when electrons move from the n-type semiconductor to the p-type, energy is absorbed at the junction, leading to a cooling effect on that side of the device. Conversely, at the junction where electrons flow from the p-type to the n-type semiconductor, heat is released, resulting in a heating effect. This bidirectional behavior enables the device to function as both a heater and cooler, depending on the current direction [24].

Thermoelectric cooling is thermodynamically reversible under the linear approximation of electric current, which allows for switching between the hot and cold sides by simply reversing the polarity of the supplied current. This reversibility is a significant advantage in compact thermal management systems where dual-mode (heating and cooling) operation is beneficial [24].

Peltier devices are widely used in applications requiring precise temperature control, such as cooling of electronic components, small-scale climate control enclosures, and portable refrigeration units. These devices are favored for their compact size, lack of moving parts, and silent operation. However, they are generally less energy-efficient compared to vapor-compression refrigeration systems and necessitate appropriate heat dissipation mechanisms to prevent thermal buildup on the hot side [24].

5. THEMPERATURE SENSOR

To ensure accurate temperature regulation, a temperature sensor is embedded in the system. These sensors convert ambient thermal conditions into readable electrical signals and are widely deployed across industries such as HVAC, biomedical, and automotive for real-time thermal monitoring [25]. The precision and responsiveness of temperature sensors are critical for safeguarding temperature-sensitive materials and maintaining system integrity.

The output from the temperature sensor is processed by a controller board, which acts as the central control unit of the system. This microcontroller-based circuit interprets sensor data, compares it to predefined temperature thresholds, and triggers appropriate control signals to the Peltier device [26]. Controller boards are pivotal in maintaining thermal equilibrium by dynamically adjusting current flow, enabling automated feedback regulation in real time. Their ability to execute complex logic routines allows for enhanced safety, stability, and energy efficiency across temperature-dependent operations.

In this experiment HiLetgo, W1209 12V DC Digital Temperature Controller Board Micro Digital Thermostat -50-

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110°C Electronic Temperature Control Module Switch with 10A One-Channel Relay and Waterproof is used. The connection diagram is as shown in Fig 7. below.

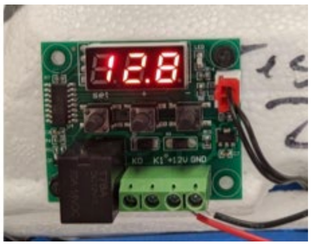

Fig 7. Digital Temperature Controller

The connection and the programming to control the temperature is done by connecting the board to the power supply. The measured temperature is displayed at all times. Press the "SET" button, press "+ or -" to set the desired temperature (long press "+ or -" to quickly increase or decrease), press "SET" to confirm the setting and return, and the controller automatically performs the relay ON/OFF. The thermostat output is 10A relay to meet a variety of high-powered loads. LED Indicator: LED off indicates the relay off; Lighting, indicates the relay is closed. Digital LED Tubes: "LL" indicates sensor open, "HH" indicates overrange, the relay will be forcibly disconnected; "---" indicates high temperature alarm Long press the "SET" button to enter the main menu settings, press "+ or -" to switching between P0-P6, then long press "SET" or 10 seconds without keystrokes to confirm the setting and return.

6. WORKING OF THE PROPOSED COOLING SYSTEM

The Peltier device was fixed to the center of the lid with adhesive thermal insulation. Both of the Peltier fans and the temperature controller inputs were connected to a constant 12V DC supply. The 12V 5A Peltier inputs were connected to a variable DC supply. The experiment was started at zero voltage, and gradually increased in steps up to 12V. The temperature, voltage, and current parameters were recorded at regular intervals. The same procedures of the experiments were repeated for the other two 12V Peltier using 12A and 6A and three such experiments were performed with the three different types of insulation inside and outside of the containers as shown in Fig 8, Fig 9, and Fig 10. The voltage, the current, the temperature, and the time parameters were recorded as shown in the Tables.

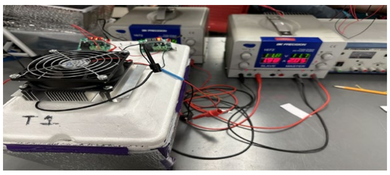

Fig 8. Model Testing of 12V 5A Peltier

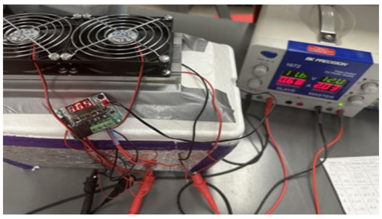

Fig 9. Model Testing of 12V 12A Peltier

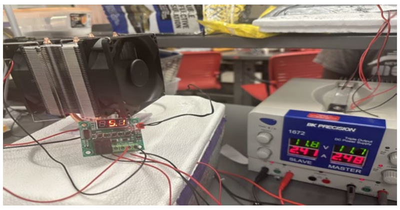

Fig 10. Model Testing of 12V 6A Peltier

Model 1 was insulated with foam and thermal insulation shield. Three 12V Peltier devices having different amperes were selected for the experiment. Test one was conducted using a 5A Peltier as seen in Fig.5, Test two was conducted using a 12A Peltier as seen in Fig.6, and Test three was conducted using a 6A Peltier as seen in Fig.7. The voltage, current, temperature and the time taken to reach the low temperature was recorded at regular intervals as shown in Table 1, Table 2, and Table 3 and is also shown in Fig11, Fig12 and Fig13 respectively.

Table 1 Results of Foam and Thermal Insulation Inside Container

Model 1 - Test 1 (12V 5A Thermoelectric Peltier)			
Voltage (V)	Current (A)	Temp (°C)	Time (Min)
0	0.00	27.5	0
2	0.41	21.2	7
4	0.74	17.1	14
6	1.04	11.6	21
8	1.38	10.9	26
10	1.69	7.5	32
12	2.34	6.0	35

Fig 11. Model 1 - Test 1 (12V 5A Thermoelectric Peltier)

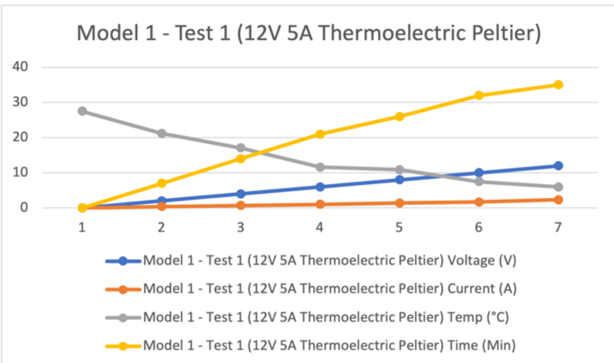

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Table 2 Results of Foam and Thermal Insulation Inside Container

Model 1 - Test 2 (12V 12A Thermoelectric Peltier)			
Voltage (V)	Current	Temp (°C)	Time (Min)
0	0.00	27.7	0
2	0.41	26.0	8
4	0.74	21.2	10
6	2.04	17.5	15
8	3.38	15.2	20
10	4.19	13.0	30
12	5.00	11.0	35

Fig 12. Model 1 - Test 2 (12V 5A Thermoelectric Peltier)

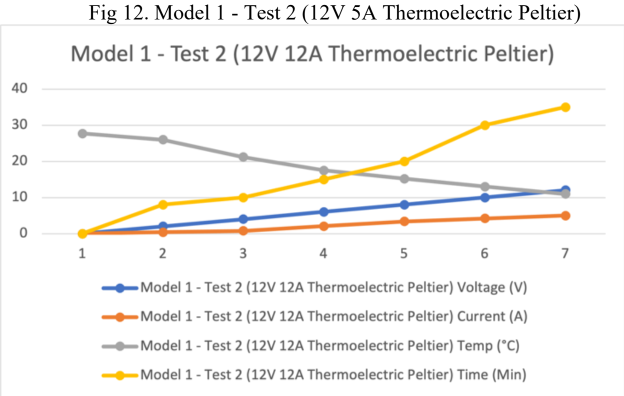
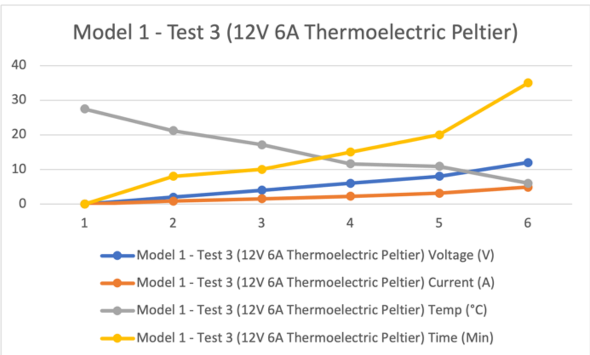


Table 3 Results of Foam and Thermal Insulation Inside Container

Model 1 - Test 3 (12V 6A Thermoelectric Peltier)			
Voltage (V)	Current (A)	Temp (°C)	Time
0	0	27.5	0
2	0.85	21.2	8
4	1.53	17.1	10
6	2.26	11.6	15
8	3.13	10.9	20
12	4.88	6	35

Fig 13. Model 1 – Test3 (12V 5A Thermoelectric Peltier)



Model 2 was insulated with double insulation consisting of reflective foam and reflective insulation on the inside and outside of the container. Three 12V Peltier devices with different amperes were used for the experiment. Test one was conducted using a 5A Peltier seen in Fig.5, Test two was conducted using a 12A Peltier seen in Fig.6, and Test three was conducted using a 6A Peltier seen in Fig.7. The voltage, current, temperature and the time taken to reach the low temperature was recorded at regular intervals seen in Table 4, Table 5, and Table 6 and is also shown in Fig14, Fig15 and Fig16 respectively.

Table 4 Results of Double Insulation Inside/Outside of Container

Model 2 - Test 1 (12V 5A Thermoelectric Peltier)			
Voltage	Current	Temp (°C)	Time (Min)
0	0	21.5	0
2	0.68	19.8	5
4	1.24	18.6	10
6	2.06	17.1	15
8	2.72	15.3	20
10	3.3	14.8	25
12	3.84	14.4	30

Fig14. Model 2 – Test 1 (12v 5a thermoelectric peltier)

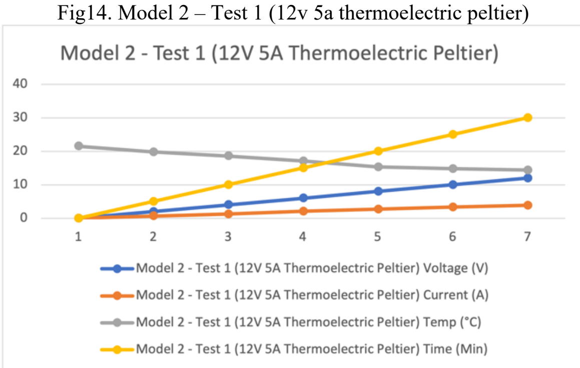


Table 5 Results of Double Insulation Inside/Outside of Container

Model 2 - Test 2 (12V 12A Thermoelectric Peltier)			
Voltage	Current	Temp (°C)	Time
0	0	20.8	0
2	0.5	14.6	5
4	1.48	12.3	10
6	2.24	8.2	15
8	2.84	4.6	20
10	3.72	1.1	25
12	4.44	-2.2	30

Fig 15. Model 2 – Test 2 (12V 5A Thermoelectric Peltier)

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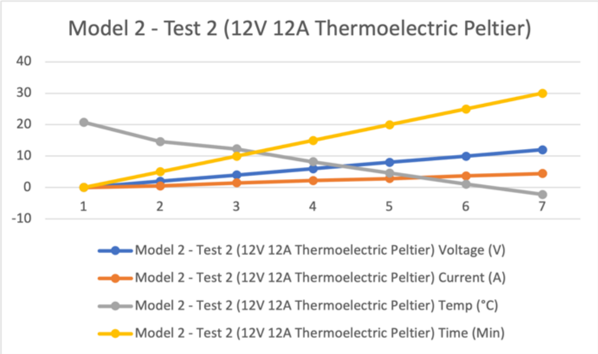
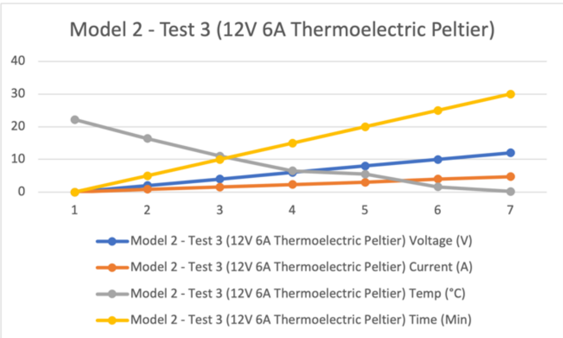


Table 6 Results of Double Insulation Inside/Outside of Container

Model 2 - Test 3 (12V 6A Thermoelectric Peltier)			
Voltage	Current	Temp (°C)	Time
0	0	22.2	0
2	0.87	16.4	5
4	1.56	11.0	10
6	2.31	6.5	15
8	3	5.5	20
10	4	1.6	25
12	4.72	0.2	30

Fig16. Model 2 – Test 3 (12V 5A Thermoelectric Peltier)



Model 3 was insulated with a layer of aluminum foil inside and outside the container. Three 12V Peltier devices were used for the experiment: Test one was conducted using a 5A Peltier seen in Fig.5, Test two was conducted using a 12A Peltier seen in Fig 6, and Test three was conducted using a 6A Peltier seen in Fig 7. The voltage, current, temperature and the time taken to reach the low temperature was recorded at regular intervals as shown in Table 7, Table 8, and Table 9 and is also shown in Fig 17, Fig 18 and Fig 19 respectively.

Table 7 Results of Aluminum Foil Inside and Outside of Container

Model 3 - Test 1 (12V 5A Thermoelectric			
Voltage	Current	Temp	Time
0	0	22.1	0
2	0.72	17.8	5
4	1.32	13.5	10
6	1.95	11	15
8	2.64	9.4	20
10	3.22	8.6	25
12	3.8	8.4	30

Fig 17. Model 3 – Test 1 (12V 5A Thermoelectric Peltier)

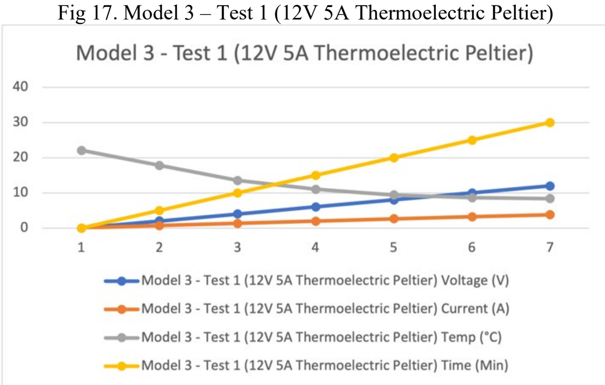


Table 8 – Results of Aluminum Foil inside/Outside of Container

Model 3 - Test 2 (12V 12A Thermoelectric			
Voltage	Current	Temp	Time
0	0	20.8	0
2	1.66	15.6	5
4	2.99	12.3	10
6	4.66	7.7	15
8	6	5.4	20
8.3	6	5.6	30

Fig18. Model 3 – Test 2 (12V 5A Thermoelectric Peltier)

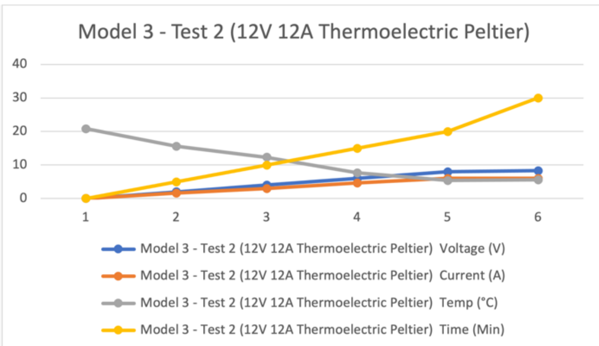


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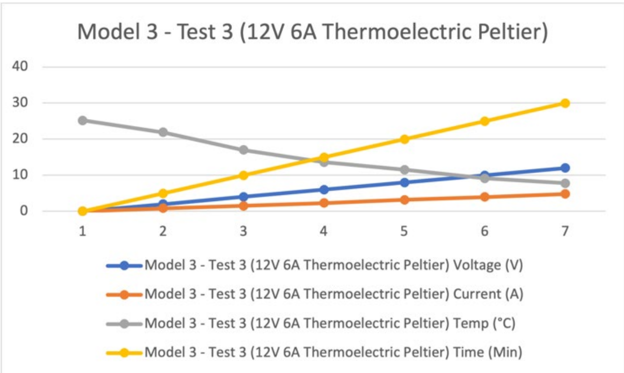
Table 9 Results of Aluminum Foil inside/Outside of Container

Model 3 - Test 3 (12V 6A Thermoelectric Peltier)			
Voltage	Current	Temp (°C)	Time
0	0	25.2	0
2	0.84	21.9	5
4	1.55	17.0	10
6	2.3	13.6	15
8	3.22	11.5	20
10	3.96	9.1	25
12	4.80	7.8	30

Fig19. Model 3 – Test 3 (12V 5A Thermoelectric Peltier)



7. RESULTS

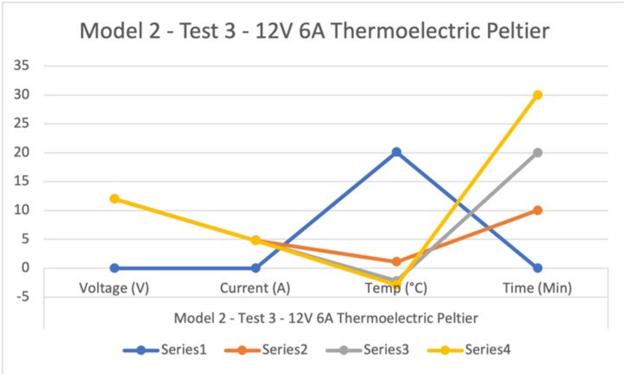
The experiment involved the utilization of a Styrofoam container equipped with three distinct types of insulation in conjunction with three varying ratings of Peltier devices. A total of nine tests were meticulously conducted, revealing that the most favorable outcome was achieved when employing a 12V 6A Peltier model in tandem with the Styrofoam container featuring dual layers of insulation. The innermost layer consisted of a reflective foam, followed by an additional layer of reflective insulation material. Conversely, the outer surface of the container was enveloped in a double layer of reflective insulation material.

During the test where the Peltier module was supplied with continuous 12V of voltage and drew a current of 4.80A, the temperature within the container plummeted to an impressive -2.9 degrees Celsius. Notably, this desired temperature was attained within a commendable timeframe of 30 minutes. This meticulous experimentation and analysis underscored the critical role of insulation and Peltier ratings in achieving optimal thermal regulation and efficiency within the Styrofoam container setup. It recorded data is shown in Table 10 and is also shown in Fig 20 respectively.

Table 10 Most Effective Results of Double Insulation of Styrofoam Container

Model 2 - Test 3 - 12V 6A Thermoelectric Peltier			
Voltage	Current (A)	Temp (°C)	Time (Min)
0	0	20.1	0
12	4.82	1.1	10
12	4.82	-2.2	20
12	4.80	-2.9	30

Fig 20. Graph Showing Results Using 12V 6A Peltier Device and Double Layers of Insulation of Styrofoam Container



VII. CONCLUSION

This experimental investigation successfully demonstrated the critical influence of insulation configuration and Peltier device specifications on the thermal regulation performance of a Styrofoam-based cooling system. Across a series of nine structured tests, various combinations of insulation layers and Peltier modules were evaluated for their ability to maintain low temperatures in a controlled environment.

The optimal thermal outcome was achieved using a 12V 6A Peltier module integrated with a dual-insulated Styrofoam container. Specifically, the use of reflective foam layered beneath double reflective insulation on both the interior and exterior surfaces of the container led to a significant reduction in internal temperature. Under these conditions, the system successfully reached a minimum of -2.9°C within 30 minutes, outperforming other configurations tested.

These results emphasize the synergistic role of advanced insulation materials and appropriately rated thermoelectric coolers in enhancing cooling efficiency. The combination of high reflectivity and low thermal conductivity in the dual insulation layers minimized heat gain from the environment, enabling the Peltier module to maintain a stable and low internal temperature with greater efficiency. The experiment underlines the necessity for careful selection of insulation architecture and Peltier device parameters in the design of portable or small-scale thermal regulation systems. These insights are valuable for applications ranging from medical

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cold chain transport to electronics cooling, where space, weight, and energy efficiency are paramount.

Future work could explore the long-term thermal stability, energy consumption analysis, and integration with smart control systems to further optimize performance and functionality in real-world scenarios.

VIII. ENGINEERING STANDARDS

We elect for our Medical Cooler Products to carry a CE Mark, and comply with the EC Directive 92/42 EEC, as a Medical Device meeting the criteria for Class 1 in Annex IX of that Directive. These Standards, unlike the World Health Organization (WHO) protocols, are recognized as having a much wider global presence than the WHO protocols.
To comply with 92/42/EEC, we are obliged to comply with these Standards:

- ANSI/ASHRAE 15-2022 - Safety Standards for Refrigeration Systems.
- EN 724:1995 - Guidance on the application of EN 46001 (ISO 9001:2008) and EN 46002 (ISO 9002) for non-active Medical Devices
- EN 980:2008 - Graphical Symbols for Medical Device Labeling
- EN 1042:2008+A1:2013 - Medical Devices, application of Risk Management
- EN ISO 11197:2009 (Formerly EN 793:1998) - Medical Supply Units
- EN 16440-1:2015 - Testing Methodologies Of Refrigerating Devices For Insulated Means Of Transport - Part 1: Mechanical Cooling Device With Forced Air Circulation Evaporator With Or Without Heating Device
- EN 46001:1997 - Specification for the application of ISO 9001 to the manufacture of Medical Devices
- IEC 16000-4-11 - Voltage dips, short interruptions and voltage variations immunity.
- IEC TC22 - Power electronic systems and equipment
- IEC TC62 - Medical equipment, software, and systems
- IES 60529 - Ingress Protection. Degrees of Protection provided by enclosures (IP Code)
- ISO 20282-1:2006 - General product safety, ease of operation and design requirements for context of use and user characteristics
- NEC Article 300 - General Requirements for Wiring Methods and Materials
- NFPA-70 (National Fire Protection Association) / NEC - Electrical Wiring Color Code Standards
- Though there are international wire color codes, the U.S. follows the National Electrical Code® (NEC). The code is identified as NFPA 70® because the NEC is sponsored by the National Fire Protection Association. Though not a federal law (states can choose to adopt it), it is approved by the American National Standards Institute (ANSI). Every three years, the NEC reviews, amends and adopts the latest code. The current NEC was last updated in 2020.

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