Thermostasis: Applied Thermoelectric Heating and Cooling for Temperature Regulation

(Technical Paper)

The Applications, Efficiency, and Impacts of Thermoelectric Cooling

(STS Paper)

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Thermal management is extremely important in numerous applications, whether it is simply for personal comfort or for the storage of life saving medical supplies. With the recent COVID pandemic, the proper storage of vaccines has a key role in rapid distribution while retaining effectiveness. According to the Centers for Disease Control and Prevention (CDC, 2022), storing vaccines outside of recommended temperature ranges would result in reduced potency or destroy the product, making it have less or no effect on the recipients. Technological applications and advancements have made more options available for managing temperature and, although the Peltier effect has been known for years, its applications are still more recent. Thermoelectric cooling devices rely on implementing this Peltier effect to create a temperature differential and then dissipating the byproduct heat, as described by (Baru, 2020). These thermoelectric refrigeration systems are often seen as an alternative to existing compressor-based refrigeration since it resolves most of the issues with the compressor systems, but the properties of these systems differ greatly.

The goal of the Technical Capstone project will be to implement a thermoelectric cooling system that is capable of setting and steadily maintaining a desired temperature for both heating and cooling. The device will use a microcontroller to control the output of multiple Peltier thermoelectric cooling modules using feedback from temperature sensors. It will also be capable of reversing the polarity to perform both heating and cooling and will be able to reach temperatures meant for storing food. This project is meant to evaluate the viability of thermoelectric devices in temperature sensitive storage environments, but also explore the versatility by using it for producing heat.

The STS research project will also discuss the applications, properties, and tradeoffs of thermoelectric cooling and evaluate the viability of thermoelectric systems. These thermoelectric systems will be compared against other existing technologies, like the more common compressor-based systems, using criteria like energy efficiency, compactness, and noise. These factors will help decide which technologies to use for given environmental and technological requirements and conditions. By outlining specific conditions and applications, the use of newer thermoelectric technologies can be used in additional suited situations that can reduce wasted materials and energy.

Technical Topic

According to the United States Food and Drug Administration, food needs to be refrigerated at or below 40 degrees Fahrenheit or 4 degrees Celsius to reduce bacteria growth (FDA, 2021). For shorter term situations, however, there are instances where food may be stored at higher temperatures for it to be readily served. In these cases, food needs to be kept at or above 140 degrees Fahrenheit or 60 degrees Celsius to keep bacteria from spreading (FDA, 2022). Most cooling devices are not able to heat as well, as the heat that is emitted as a byproduct. This technical project is meant to evaluate an application of thermoelectric cooling with specific requirements. These requirements specify that the device must be able to cool a small environment at refrigeration temperatures or below and capable of performing heating. To evaluate the cooling rate, it must be able to reach a specified temperature within a given amount of time, while maintaining the stability of that temperature within a specified tolerance range. The energy efficiency of the device must also be sufficient to maintain a constant output with a limited power supply for a specified period.

To perform both cooling and heating, other devices may need separate hardware and may also require a rework on a sizable portion of the earlier design. Peltier thermoelectric devices are more versatile since the functionality of heating and cooling can be swapped electrically. This can be achieved by including an H bridge in the circuit that flips the polarity of the voltage and the direction of current through the Peltier module. This H bridge makes use of Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) and gate drivers to effectively serve as switches for supplying power to the device.

One of the concerns with temperature regulating devices is the speed and stability for reaching a specific temperature. A common phenomenon with many devices is an overshot of the target temperature before it reaches a stable temperature and then an oscillation around the desired temperature. While the impact may not be as significant for the storage of food as for other applications, such as storing medical supplies, it is important to evaluate the viability for maintaining a stable temperature. To achieve this goal, the Peltier modules will be controlled using a microcontroller with a fuzzy logic algorithm that uses real-time temperature feedback to produce an expected current output. A fuzzy logic algorithm will be developed because, according to research by Indiketiya (2021), a Fuzzy Logic control algorithm reaches a stable temperature quicker than other approaches, such as Proportional Integral Derivative (PID) based, or Error based control algorithms.

The current output from the fuzzy control algorithm ranges outside the capabilities of the microcontroller. To achieve the same effect, the output of the microcontroller will be the equivalent signal using Pulse Width Modulation (PWM), producing a voltage to allow current to pass through a MOSFET. The transistors of the previously mentioned H-bridge will be used to perform both functions. The duty cycle of the PWM signal will be adjusted to produce an average current equal to the desired output current. The peltier devices, however, are known to be less efficient when using an unfiltered PWM signal than if a Direct Current (DC) signal were to be applied (*Peltier Element Efficiency*). To filter the PWM signal, an appropriately sized inductor will be used in conjunction with the duty cycle switching frequency that will produce a more stable current.

The project specifications will be re-evaluated based on a performance report of the completed device. This may include information concerning power efficiency, battery life under various conditions, rate of thermal transfer, maximum temperature differentials, temperature ranges with various ambient temperatures, and temperature fluctuation ranges or stability. The performance outcomes can be compared against other forms of cooling technology providing a realistic perspective on uses for thermoelectric devices while also devising improvements upon current designs.

STS Discussion

Thermoelectric devices making use of the Peltier effect can create a temperature differential when an electric current is applied, but the Peltier effect can also be reversed and create an electric current when a temperature differential is created. According to Baru and Bhatia (2020), these devices are dependable since their operation does not require moving parts while also being versatile with its application for energy generation in environments with otherwise unusable byproduct heat. Navarro-Peris, et al. (2015), explored this use by applying the Peltier devices to make existing Compressor cooling devices more efficient. This application used the Peltier devices as thermoelectric generators, converting thermal energy from the byproduct heat of the compressor into electrical energy, but the efficiency, ranging from 1.5 - 1%, leaves much to be desired.

Compressor-based cooling technology makes use of coolants that can efficiently absorb thermal energy until the transition from its liquid state to its gaseous state; the coolant is then converted back into its liquid state by applying pressure. As a result of this process, compressor cooling devices make use of several moving parts which increase noise generation and reduce the reliability of the device *(Thermoelectric Coolers).* These less-desirable traits are not entirely excluded from Peltier devices, contrary to the statement of Baru and Bhatia (2020); while moving parts are not mandatory to perform the basic functions of thermoelectric cooling, the byproduct heat still needs to be eliminated. Most commonly, this involves the use of a heatsink combined with forced air convection or liquid cooling to dissipate the heat. The size of the compressor systems is still much larger than most thermoelectric systems, but compressor cooling systems can remove much more heat and are not heavily reliant upon the ambient temperature. A thermoelectric module's performance is dependent on the ambient temperature since it can only create a temperature differential.

Thermoelectric devices using the Peltier effect create a temperature differential, so the ambient temperature limits the overall performance. This restriction from the ambient temperature sets a condition for the temperature ranges at which it can work, but it is not entirely restricted to a single device. Kamasi, et al. (2015) explored how multiple Peltier devices can be used together to reduce the temperature limitations and make it usable in more applications. By stacking Peltier devices, the temperature ranges are expanded since the temperature of the stacked hot side is actively being cooled and can reach temperatures below the ambient. Since these devices do generate their own heat, the thermal output of these devices needs to be reduced as more modules are stacked and the inclusion of more modules also requires more power to function; in the graphs from the experiment performed by Kamasi, et al. (2015), more layers of thermoelectric cooling modules increased the temperature differential, but it was only increased by around two degrees Celsius. This impact, while important, may not be efficient enough to compensate for the tradeoff of increased power consumption.

The energy consumption and scaling of thermoelectric devices may not seem to be ideal for large scale applications or for more extreme cases, but not all applications have been explored. The strengths of these devices lie in their versatility and smaller size. The paper by Zaferani, et al (2021) lists several of the unique properties and how they can be applied for use in the medical field. These applications ranged from the stable transport of medical supplies to localized hypothermia for surgery. There was also the inclusion of cryotherapy and treatments in the dermatology field for skin treatment. The development of flexible and wearable thermoelectric generators is in development and, with the advancement of other technology, like 3D printing, these thermoelectric devices may be applied in more effective ways.

Conclusion

Thermoelectric technology is not the replacement for most current compressor-based cooling systems, but it can be applied in many of the smaller scale thermal applications that a compressor system is too large or volatile to manage. Thermoelectric cooling systems may have a more limited range of conditions to be used effectively but offer more stable control and on a smaller scale. Thermoelectric devices can also be used as a thermoelectric generator, opening many unique applications that can be explored and expanded upon over time to have greater efficiency.

Thermoelectric technology is not necessarily as effective in all thermal applications, so the use cases need to be carefully considered. These devices have more unique or small-scale applications and require precision for more efficient operation; inefficient use can lead to increased power consumption, damage to the device, and a waste of materials. More exploration, refinement, and development may be necessary for effective application of thermoelectric generation.

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