Project about a 'Miniature freezer' focusing on Optimizing Multiple Layered Thermoelectric Modules for maximum efficiency and cooling performance

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Written by Junghoon Lee

I. Introduction

This project was to make a tiny freezer that is yet big enough to be functional. Here I would like to share my experiences in making a miniature-sized (93x96x116mm) functional refrigerator, specifically optimizing variables like, different TEC size, stacking, voltage and current adjustments, simultaneously minimizing heat dissipation, and maximizing cooling performance.

There are lots of methods of cooling and a variety of cooling systems that are known and can be chosen from. In order to satisfy the condition that it would be compacted in a very small space (and cost effectiveness was also a factor), I decided to use thermoelectric module cooler (TEC) for my cooling apparatus.

TECs are simply solid state heat pumps. They move heat from one side to the other, causing one side to be hot whereas the other side cold. TECs do not have a fixed or rated temperature when applied power, which means that TEC modules could be stacked to achieve lower temperatures.

II. Initial Tests

The desirable cooling system should be as small as possible. For this reason, I started with the smallest heat sink yet big enough to remove heat effectively from a

TEC surface, and gradually increased in size. The thermal conductivity of the thermal paste I used for the primary tests were 1.42W/m-k and for the 4^{th} 9.2W/m-k. The test was all done in a room of 23~25 degrees C.

The first test was performed with 45x60x24mm heat sink, 3030 12V 4A TEC, and 40x10 fan. I was able to achieve the maximum of -7 degrees C at 12V 2.5A. However, when more than 2.5A was applied, the cold side was rising in temperature. I ran a thermal simulation with the heat sink and TEC (heat source) to analyze what is causing the rise of temperature when the applied current was exceeding 2.5A. After analyzing the simulation, I was able to see that there was no significant temperature difference between the hottest and coldest area of the heat sink. This concludes to a poor cooling performance of the heat sink. I also ran a CFD (computational fluid dynamics) simulation to analyze the forced convection heat flow and internal/external air currents. Due to the small heat sink leading to poor cooling, the temperature of air exiting the heat sink fins was around 110C (highest temperature possible). It was exceeding the glass transition temperature (transition from rigid state to more flexible state) of PLA (polylactic acid) around 50~80C, which is the material of the heat sink enclosure. To get an idea of the internal temperature with an enclosure, a cube enclosure (50x35x30mm) with 6mm thick foam was added to contain the cool air inside the cube. But it was no way near my targeted temperature which is below freezing.

The second test was performed with 90x60x24mm heat sink and two 40x10 fan, which is double the size in length of the 45x60x25, and 3030 TEC 12V 2.6A. With this setup I could get almost double the temperature, that is -13C, but still that was not enough to produce sufficient cooling. I realized that signal stage TEC was not able to cool the cube enclosure below freezing temperature.

The third test was performed with dual stage TECs, 100x95x24 heat sink, 4040 TEC 12V 4A for the bottom layer and 3030 TEC 12V 4A on the top of the bottom layer, 92x38 fan was used.

With the 4040 TEC 12V 2.6A and 3030 TEC 5V 1A, I was able to get -23C, roughly 36W for both TECs. I designed a small enclosure (40x35x35mm) to measure the chamber temperature. With the same test setup mentioned above, I added a 30x30x10 heat sink to the cold side of the 3030 TEC. Despite the surface temperature of -23C, the lowest chamber temperature I was able to achieve was 4 degrees lower than ambient temperature. Soon I realized it was due to the lack of a fan inside the chamber to circulate the cooled air. After adding a 25x25x10 fan on top of the cold side heat sink, I was able to get a lowest temperature of -5C, which was much lower than before.

However, a problem came up with the size of the heat sink. The heat sink of 100x95x24 that I tested was too big to be used for the miniature-sized fridge. Therefore, I had to optimize the size of the heat sink for it to satisfy the cooling capacity, mostly by trial and error method.

Lastly, I got three different heat sinks 92x92x30, 77x77x30, and 85x85x44. After some tests, 77x77x30 heat sink proved to be the exact form factor for my design, namely 77x77x30 heat sink with 80x10 fan. I did a test with the same setup as the 3rd test (4040 TEC on bottom, 3030 TEC on top). With the 4040 TEC at 12V 2.6A and 3030 TEC at 6V 1A, minimum temperature I was able to get was -24C. This was the value that I was able to get when the TEC module layers were placed at the center of the heat sink. I wondered what temperatures I could get by off centering the TEC module layers. I located the TEC module layers off-centered from the center of the fan. By off-centering the TEC module layers, I could get the lowest of -27C! I didn’t expect the temperature to drop even lower than -24C, off-targeting my presumption that there must be an increase in temperature. After hours trying to find out what is causing this unexpected phenomenon, I concluded that it was caused by the difference in air flow. Due to the physical and design limitations of a axial DC fan, where the motor is placed in the center of the fan, causing the center with no air velocity, only the surface with the blades would have air flow. For example, when axial fans are used with heat sinks that are the same size and the heat source is in the center of the heat sink, air would be only forced by the fan blades. Because of this, there would be lack of air at the middle, where the heat is most concentrated. Lack of air flow at the hottest area would be undesirable and have poor cooling performance.

By knowing I was able to get a chamber temperature well below freezing at -23C, I was sure that I would get the same, if not lower at -27C.

III.Setting up the Fridge

A. 3D Design

I started designing the heat sink, followed by other components. The design process took a while because I needed it to be very small, had to be 3D printable, modular enough to be assembled with ease, and most importantly, it had to be designed for maximum efficiency (Highest COP possible), which in my case was minimizing any temperature rise in the cold chamber.

B. Electronics

I wanted a display to monitor the system information and temperature. A 0.96 inch OLED display and Arduino Nano was used. For my project, “The smaller the better” I had two small sensors to choose from, which were AHT10 (digital) and KY013 (analog) sensors. I wired the AHT10 to an Arduino Nano via I2C, printing values to the serial monitor to see if I could get correct measurements. It was a perfect choice, until I realized that the AHT10 breakout module had SMD components that could not be used at a freezing temperature. Moreover, AHT10 was designed to measure space/chamber temperature, not to measure surface temperature. The only sensor left on my list was the KY013 analog sensor. Same as before, I connected the KY013 sensor to an Arduino Nano. Using the serial print, I was able to get a reliable temperature reading. This temperature sensor is a NTC thermistor, which changes its resistance value when applied to different temperatures. According to the specifications of the thermistor, it has a temperature range of -55C to 125C, which is well above my temperature range. After making sure the sensor is working properly, I needed two sensors for the cold chamber and the hot side of the heat sink. Both sensors should display the real time values using the OLED display. I've wired the two sensors, OLED and an Arduino Nano. After uploading the finished code to the Nano, I had a problem that the two temperature values displayed on the OLED were off by a lot. After few days of troubleshooting, I finally found out that the I2C connection with the OLED and the Arduino Nano A4 and A5 pins was causing the problem. I switched to the SPI version of the OLED, by which I could solve the problem. I wasn't sure why the I2C connection was causing the problem, but I assumed it was due to the I2C bus on the analog pins interfering with the analog read or it could be a library issue. I later added a "warning" prompt when the hot side heat sink temperature rises above 50C.

C. TEC control

I needed a different voltage and current to drive the two TEC modules. PWM control would be the easiest to drive the TECs but, after some searching on the web, I found out that TECs operate its max efficiency, when given constant voltage and constant current. However, I wasn't able to find a controller that could output constant V, A. I could find some controllers that are specialized in controlling TECs, but the price was a couple of hundred dollars. I instead thought about using an adjustable voltage and current buck converter with MCP4725 DACs to convert digital signal from an Arduino to analog voltage and feed it to the pins where the adjustable potentiometer for adjusting V, A are connected. But soon realized that I was going too far with the electronics, it just made things more complex. I decided to reserve this for my second revision of this project. Using my DMM, I set both voltage and current for the two TEC modules, 4040 at 12V 2.6A, 3030 at 6V 1A. After I checked that everything was working properly, I started to assemble the fridge. The wires for the electronics were a challenge to fit inside the case, but other than that everything came together, with minimal design changes. I used a 12V 5A power supply for the power. Powered on, after few minutes, the cold chamber went down to -6.6C at 24C ambient temperature. To make sure it's a "real freezer", I added some water inside the chamber. As expected the water froze within 15~20 minutes.

IV. Conclusion

This project took me around 30 days to build. Roughly 25 days for the experiment and design, 8 days for the electronics and assembly. The experiments took the longest from my perspective. I think it's due to the delay in acquiring new parts to be shipped.

I'm very thankful because this project was working as planned. In the course of this project, I've learned about cooling, 3D design, CFD (computational fluid dynamics), simulation, animation, and a lot more. There were some times I wanted to trash what I was working on. But I could overcome this with hope and tenacity inside of me. So I've learned that if I put in enough time and hold on to a problem until it has been solved, I think it's worth every second that I invest in what I'm working on.

Appendix: Additional comments on this project

1. Forced convection with DC fan and heat sink

Due to the physical and design limitations of a axial DC fan, where the motor is placed in the center of the fan, causing the center with no air velocity, only the surface with the blades would have air flow. For example, when axial fans are used with heat sinks that are the same size and the heat source is in the center of the heat sink. Air would be only forced by the fan blades. Because of this, there would be lack of air at the middle, where the heat is most concentrated. Lack of air flow at the hottest area would be undesirable and have poor cooling performance.

*This can be improved by

-Redesigning the heat sink (fins) to redirect the air flow where the heat is most concentrated

-Using a blower (centrifugal blower) fan would be an option to maximize the area with air flow/area with no air flow

2. Closely packed vs. Widely spaced fins for a given base area

*Closely packed fins

-Pros: Greater surface area for heat transfer

-Cons: Smaller heat transfer coefficient, due to the extra resistance the additional fins introduce to fluid flow through the inter-fin passages

*Widely spaced fins

-Pros: Higher heat transfer coefficient

-Cons: Smaller surface area

*Conclusion

-Optimum spacing that maximizes natural and forced convection Heat transfer from the heat sink for a given size

3. Natural vs Forced convection/Heat sink size

-Forced convection is more effective

-Smaller heat sink = total smaller size

-Width (fin count): double width = 2 times increase in heat dissipation

-Height (parallel to heat source): double fin height = 1.4 times increase in heat dissipation

*Conclusion

-More effective to increase width rather than height

4. Thermal runaway

-Describes a process that is accelerated by increased temperature, in turn releasing energy that further increases temperature

-Coefficient of performance (COP)

-COP is a measure of efficiency, the ratio between removed heat and supplied power

-COP = heat pumped / electrical power

-Lower performance of Peltier element when using PWM. Use DC current, less overall waste heat is generated