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Design and Construction of a Thermoacoustic Refrigerator

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DESIGN AND CONSTRUCTION OF A THERMOACOUSTIC REFRIGERATOR

A Major Qualifying Project Report:
submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science
by

______________________________
Meghan Labounty

______________________________
Andrew Lingenfelter

Date: April 23, 2008

Approved:

______________________________
Professor Germano S. Iannacchione, Advisor

1. Thermoacoustics
2. Refrigerator

This report represents the work of one or more WPI undergraduate students
Submitted to the faculty as evidence of completion of a degree requirement.
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Abstract

A thermoacoustic refrigerator was designed, built and tested. A maximum normalized temperature difference of 7.564 K was recorded across the stack. Heat generated by the resistance in the speaker affected the results. Despite these effects, much of the temperature difference recorded was determined to be due to thermoacoustic refrigeration.
Acknowledgements

We would like to thank Professor Iannacchione for advising our project and for giving us so much help during our project. We would also like to thank Roger Steele for doing the machining that our project required. We would also like to thank the graduate students in our lab for their help on anything from finding something in the lab to teaching us how to solder.
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1 Background

Acoustics has an extensive history, but it was not until the mid 1800s that the connection between heat and sound was made. That connection produced curiosity about the oscillating heat transfer between gas sound waves and solid boundaries, initiating advanced research in thermoacoustics (Swift, A Brief Description 1). Physicists determined that the interaction between sound and air is too small to measure, however sound waves in pressurized gas have the power to create intense thermoacoustic interactions. These interactions have the ability to power potentially energy efficient thermoacoustic devices, motivating the continued interest in thermoacoustic improvement.

1.1 History of Thermoacoustics

In his 1686 work *Principia*, Newton included a mechanical interpretation of sound as being pressure pulses transmitted through neighboring fluid particles. Newton thought these expansions and compressions happened without affecting the temperature, while in fact they do produce slight variations in temperature as found by Laplace. This was observed by 19th-century glassblowers who noticed that as the glass was heated up sound was produced (Garrett). This made people wonder if a change temperature could produce sound, could sound produce a change in temperature?
In the mid 1800s, Rijke and Sondhaus made numerous discoveries significantly progressing the study of thermoacoustics. Rijke determined that a large vertical tube, open at both ends, emitted sound when heat was placed at one quarter of the tube length. Additionally, Sondhaus described how a tube closed at one end will produce sound when the closed end is heated. In 1975, Merkli and Thomann were able to observe sound producing a temperature difference (Symko, 646). Rott researched these effects and developed the mathematics describing oscillations in a tube with a temperature gradient (Swift, Unifying Perspective 2380). These results confirmed the connection between sound and heat.

In 1983, Wheatley developed a thermoacoustic refrigerator, which produced a temperature difference of 100 °C when pumped with sound at 500 Hz at a level above 185 dB in pressurized helium gas (Symko, 648). Five years later, Hofler invented a standing-wave thermoacoustic refrigerator, confirming the validity and accuracy of Rott’s approach to acoustics in small channels (Swift, A Brief Description 1).

The Space ThermoAcoustic Refrigerator (STAR) was the first electrically-driven thermoacoustic chiller designed to operate outside a laboratory. It was launched on the Space Shuttle Discovery (STS-42) on January 22, 1992. Developed and tested at the Naval Postgraduate School in Monterey, CA, it has the ability to move five watts of heat and exhibited a peak Carnot efficiency of 20% across the stack (Penn State).
In 1995, the Shipboard Electronics ThermoAcoustic Chiller was used to cool electronics on board the USS Deyo, a Spruance-class destroyer in the Atlantic Fleet. While at sea, it produced a maximum cooling power of 419 watts and at the lowest temperature which could be achieved using water as the heat exchanging fluid, it produced 294 watts of useful cooling. It exhibited a peak Carnot efficiency of 17% (Penn State).

In 2004, Penn State and Ben & Jerry’s teamed up to produce a working thermoacoustic chiller. The refrigerator was debuted at Ben & Jerry’s in Manhattan on Earth Day. The device successfully kept the ice cream cold by using helium and a 190 dB loudspeaker that fluctuated 100 times per second (Lurie). Although 190 dB would damage a human ear, the thermoacoustic refrigerator is completely enclosed and all that can be heard is a gentle hum similar and sometimes quieter than that of a conventional refrigerator.

### 1.2 Importance

The importance of thermoacoustic refrigeration is growing every day. Despite the face that thermoacoustic refrigerators are not as efficient as conventional ones, there are many other advantages to consider. With continuous technological advancements, thermoacoustic refrigerators may one day become as, if not more efficient than conventional refrigerators.
1.2.1 Efficiency vs. Other Methods

Unfortunately, thermoacoustic refrigerators are not highly efficient when compared with vapor compression refrigerators. At the present time, the most efficient thermoacoustic refrigerators have Carnot efficiencies between 20-30% which is half that of the conventional counterpart (Penn State). However, higher efficiencies are possible if power density is sacrificed or if a mixture of helium and heavier inert gases is used (Swift, Unifying Perspective 2379). For a project with a small-scale design, the lack of moving parts should lead to a higher efficiency.

Despite the efficiency problem, for applications such as space cooling it may not be an issue. Thermoacoustic refrigeration is highly useful for niche applications where efficiency is not a major concern. However, as thermoacoustics is advancing and growing, the efficiency of new devices continues to increase creating a greater application and need for the technology.

1.2.2 Improvements

Although there is great potential for thermoacoustic refrigeration, there are still improvements to be made to make thermoacoustic devices more efficient and useful. Since recent designs of thermoacoustic refrigerators lack in efficiency it would currently not be worthwhile produce a refrigerator that consumes twice electricity as its conventional prototypes (Pinholster, 756). However, with time, improvements in heat exchangers and other thermoacoustic components should increase efficiency so that it is comparable with conventional systems.
Thermoacoustic efficiency is further hindered by friction and distortion. The friction of the gas molecules within the resonator limit the total efficiency that can be achieved by the device. Losses due to acoustic distortion occurring over 155 dB further decrease the efficiency of the system. Focusing on efficiency will allow thermoacoustic refrigerators to become the future of energy saving machines.

1.2.3 Future

There are countless possibilities for the future of thermoacoustic refrigeration devices since it is an emerging technology and advances are being made with each new device. Not only do thermoacoustic refrigerators have practical applications as conventional domestic food refrigerators and freezers but they also offer a lot to cryogenics, the liquification of natural gasses and spacecraft applications (Swift, Unifying Perspective 2379). Niche industries, such as these, would greatly benefit from a cleaner and more economical source of energy. Because of these exciting possibilities there is an increase in companies independently designing devices for future use.

Peavey Electronics of Meridian, Mississippi, and Cardinal Research Corporation of Richmond, Virginia plan to utilize thermoacoustic refrigerators for fishing boats and marine vessels. Cool Sound Industries of Port St. Lucie, Florida is looking to develop thermoacoustic air conditioning systems for homes and office buildings, which with proper funding could be available on the market in less than two years (Pinholster, 757).
Steve Garrett and Matt Poese, co-creators of the Ben & Jerry’s project hope to mass produce the thermoacoustic chiller in three to five years for specialty purposes (Penn State). The benefits of which include little environmental harm, low noise pollution, and reliability since there are few moving parts.

1.2.4 Implications

There are many important implications that would come from the creation and widespread use of thermoacoustic refrigerators. Research and progress made in the field would greatly benefit the energy industry. Thermoacoustic refrigerators have the great potential to be environmentally friendly, quiet and a reliable source of energy (Tijani, Design 50). They do not heavily rely on valuable fossil fuels like conventional refrigerators; the mass production of efficient devices would greatly decrease the world’s dependence on such resources. Also, thermoacoustic refrigerators have simplistic designs and can be produced using few moving parts minimizing overall costs (Tijani, Construction 60).

There is much to be gained from the use and mass production of efficient thermoacoustic refrigerators. Unlike with classical engines, there are no sliding seals or lubrication, which is achieved because of the few moving components (Tijani, Construction 61). As a result high powers and energies can be achieved from little pressure displacement within the thermoacoustic refrigerator. They also have very few moving parts. In an
electrically driven thermoacoustic refrigerator there is only one moving component, the speaker. In a thermally driven device there are none (Tijani, Construction 61).

Unlike with other machines, thermoacoustic refrigerators are powered by gasses and need no working fluids for a temperature change. The benefit of using a gas such as helium is that it is non toxic, non flammable, and not hazardous to the environment. Unlike with harmful hydroflouocarbons and dangerous greenhouse gasses, helium simply drifts into space, rather than being trapped in Earth’s atmosphere. Helium is also the most practical gas to use with thermoacoustic refrigeration since it has the highest sound velocity and thermal conductivity of the inert gasses and is cheap compared to other noble gasses (Tijani, Construction 63).

Other benefits of thermoacoustic refrigeration include cooling power and immaturity. These devices are intrinsically suited to proportional control meaning that their cooling power is continuously variable (Tijani, Construction 64). Unlike with conventional refrigerators, thermoacoustic refrigerators are not constantly running and since they can be controlled better they waste less energy. Also, thermoacoustics is the youngest of the heat engine cycles. Since it is recent compared to other methods, there is a greater chance for breakthroughs in performance and manufacturability.

1.3 Our Interest

Andrew and Meghan were introduced to the idea of thermoacoustics by Professor Iannacchione. He showed them a previous Major Qualifying Project that another student,
Matthew Hilt, completed in 2002 in which he designed and built a thermoacoustic refrigerator. Both students felt that thermoacoustics was a very interesting topic. The fact that you could change the temperature of things using sound was very fascinating.

Andrew and Meghan are also interested in the implications that an efficient thermoacoustic refrigerator would have on the world. Since thermoacoustics is an emerging technology, it has great potential to become a great new source for energy for many different applications. The designs and functions of these devices are evolving every day and as they change and become better they offer the world not only an environmentally friendly means of energy, but a more reliable and cheaper source. Thermoacoustic refrigerators would not only be an improvement to conventional refrigeration devices, but that they could be used in combination with engines and other technologies is exciting in that it would revolutionize that way we consume and use valuable natural resources.

1.3.1 Personal Goals

In addition to the interesting aspects of thermoacoustics and its useful applications in the world, the project also meets the personal goals of Andrew and Meghan. Andrew is very interested in thermodynamics. He plans to pursue a career in nuclear reactor research and design and feels that this project will allow him to gain some background in thermodynamics that may be helpful in his future endeavors. Meghan is particularly interested in the niche applications of thermoacoustic refrigerators. The implications for
the space industry are especially intriguing to Meghan since she aspires to work in astrophysics someday.

As well as learning about thermoacoustics and its many applications, Andrew and Meghan hope to benefit from the entire project experience. Working on an experimental project will greatly assist Andrew and Meghan in any future endeavors in which they will be researching and problem solving. Not only will they be able to grow as independent thinkers, but they will also obtain required collaborative skills, which will be useful when working on projects in the future.

### 1.4 How It Works

Most of the theory behind thermoacoustic refrigeration is just simple concepts that most students learn in their introductory physics or chemistry classes. The concepts are the Ideal Gas Law and how sound waves act in an open-ended tube.

#### 1.4.1 General Theory

The theory behind thermoacoustic refrigerators rests mainly on Boyle’s Law of gases governed by Equation 1:

\[ PV = nRT \quad (1) \]

Where \( P \) is the pressure, \( V \) is the volume, \( n \) is the number of moles of molecules, \( R \) is Rydberg’s constant 8.3145 J / mol K and \( T \) is temperature. Inside a closed container, \( V \) and \( n \) stay constant. Therefore if pressure oscillations are created under these conditions,
the temperature will also oscillate. The pressure oscillations can be created by sounds waves driven by a speaker. These changes in temperature can be exploited to pump heat from a cold area to a hot area. This creates refrigeration with the use of sound waves, commonly known as thermoacoustic refrigeration.

To promote thermoacoustic refrigeration there are several main components that are involved. There is the resonator, the stack, heat exchangers, and the frequency generator. The frequency generator oscillates to create pressure displacements in the closed container. A common frequency generator is an electromechanical speaker. The stack is used to thermally isolate the gas particles from the outside environment to allow the adiabatic transport of heat from one heat exchanger to the other. The resonator is used to house the sound waves with minimum acoustical dissipation. Also, the resonator must be thermally insulated at the stack to prevent heat loss during thermoacoustic heat pumping.

In a thermoacoustic refrigerator, externally applied work transfers heat from the lower temperature reservoir to the higher temperature reservoir, where the external work is supplied by the standing sound wave in the resonator. The standing wave makes the gas parcels oscillate back and forth parallel to the walls of the stack. This changing compression and rarefaction of the gas makes the local temperature of the gas oscillate from the adiabatic nature of the sound waves. When the local temperature of the gas becomes larger than that of the stack wall, the heats is transferred from the gas parcel to the stack wall. Once the temperature becomes lower than that of the actual stack wall, the heat is completely transferred from the wall to the gas parcel.
No heat is transferred along the stack when the peak-to-peak temperature variation caused by adiabatic compression of the gas is the same as local wall temperature. However, when the sound wave temperature variation of the gas parcel is greater than the longitudinal temperature gradient,

$$T_{\text{crit}} = \frac{p}{\xi \rho c_p} \quad (2)$$

Heat will be transferred between the hot and cold ends of the stack from the lower temperature to the higher temperature causing refrigeration, where $p$ and $\xi$ are the acoustic pressure and displacement amplitudes of the sound wave.

In general, as the longitudinal sound wave forces a gas parcel to move towards the closed end of the tube the gas is compressed as a direct result of the increase in pressure. The compression of the gas causes an increase in the temperature of the parcel making it hotter than the stack wall. As a result the stack wall absorbs the extra heat from the gas causing the parcel to reduce in volume. The gas parcel is then pushed towards the areas of lower pressure where it can than absorb heat from the stack walls and expand.

The cycle of giving away and absorbing heat to and from the stack continues along the tube. As a result, a small amount of heat is moved the short distance along the stack from the cooler to the warmer end. This relay of gas parcels in turn moves a large amount of heat from one end of the stack to the other in very small increments.
1.4.2 Components Involved

There are several main components involved in a thermoacoustic refrigerator. The main components are the stack, heat exchangers and resonator. Each of these components has a specific purpose in thermoacoustic refrigeration.

1.4.2.1 Stack

The stack of a thermoacoustic refrigerator is a thin walled tube with thin, well-spaced plates aligned parallel to the tube axis. The addition of more plates to the stack increases the thermal exchange area, leading to an increased amount of heat flux and thus an increased overall efficiency of the device.

The spacing between the plates in the stack is crucial in a properly functioning device. If the spacing between the plates is too narrow the good thermal contact between the gas and the stack keeps the gas at a temperature similar to the stack. If the spacing is too wide much of the gas is in poor thermal contact with the stack and does not transfer heat effectively to and from the stack. However, when the temperature difference across the stack is large enough, the air in the tube oscillates spontaneously.

The primary constraint in designing the stack is that the layers need to be a few thermal penetration depths apart, with four thermal penetration depths being the optimum layer separation. Where thermal penetration depth, \( \delta_k \), is defined as the distance that heat can diffuse through a gas during the time given by Equation 3,

\[
t = \frac{51}{\pi f} \quad (3)
\]
Where $f$ is the frequency of the standing wave. $\delta_k$ depends on the thermal conductivity, $k$, the density of the gas, $\rho$, and the isobaric specific heat per unit mass, $c_p$, according to Equation 4,

$$\delta_k = \sqrt{k/\pi f \rho c_p} \quad (4)$$

For our purposes, we can assume a “short stack approximation” since the stack is short enough that it does not perturb the standing wave shown by Equation 5,

$$P_1 = P_A \sin(x/\lambda) = p_1^s \quad (5)$$

In order to ensure proper thermal interaction between the speaker and the stack, a non-conductive material such as Mylar, PVC piping or Kapton, a polyimide film, should be used. If a conductive material such as copper is used, the temperature difference between the speaker and resonator will be very small and thus hard to detect.

### 1.4.2.2 Heat Exchanger

The heat exchangers function as a heat pump, driven by the acoustic work produced from the stack. Heat exchangers are attached to both ends of the stack. The cold heat exchanger removes heat from the cold temperature reservoir $T_r$ and moves that heat to the cold side of the stack at a temperature $T_c$. The heat exchanger at temperature $T_h$ rejects the pumped heat from the cold heat exchanger and the absorbed acoustic work, which is at temperature $T_c$. Without the heat exchangers, heat would neither be supplied nor extracted from the ends of the stack. The heat exchanger strips and the nearby stack plates are nonparallel to each other in order to prevent the total blockage of any gaps in the stack by a heat exchanger strip.
Once the hot heat exchanger temperature is high enough for the parcel of gas to oscillate, the cold heat exchanger can cool to below 0°C as the heat is pumped from the cold heat exchanger to that of the room temperature exchanger.

In order to achieve optimum performance, the heat exchanger must be as long as the peak-to-peak displacement amplitude:

\[
2\frac{u_l}{\omega}
\] (6)

Where \( u \) is the x-component of the velocity of the longitudinal wave and \( \omega \) is the enthalpy per unit mass. When a heat exchanger is too long, some parcels of fluid only come into contact with the ends of the heat exchanger and when it is too short parcels can jump past the heat exchanger (Swift, TA Engines 1145). Both of which serve no purpose and are ineffective in transporting heat. Although Equation 6 for the heat exchanger length is ideal for this project it is imprecise by \( \delta_k \), which is the distance heat can diffuse longitudinally past the ends of the heat exchanger. Poor performance of heat exchangers leads to lower efficiencies in thermoacoustic refrigerators.

1.4.2.3 Resonator

The resonator is composed of three main parts: the tube, buffer volume, and speaker housing. The resonator needs to be designed in such a way that is compact, light and strong. It must also impede the dissipation of acoustical energy as much as possible. The amount of acoustical power lost per unit of surface area of the resonator is given by Equation 7,
\[ \frac{d\hat{W}_j}{d\xi} = \frac{1}{4} \rho m |u_j|^2 \delta_{j,\omega} + \frac{1}{4} \frac{|p_j|^2}{\rho m a^2} (\gamma - 1) \delta_{j,\omega}, \]  

(7)

Where \( \rho \) is the density and \( \delta \) is the thermal penetration depth (Tijani, Design 54).

The first consideration is the length of the resonator. The length of the resonator should be a quarter that of the wavelength. A quarter-wavelength resonator will dissipate only half the energy dissipated by the half-wavelength resonator (Swift, TA Engines 1147 and Swift, Loudspeaker TAR 103).

Another consideration is the shape and size of the different resonator components. Original designs simulated an open-end resonator by using a spherical buffer volume. Not only is this complicated to manufacture, but also it is also not optimal. Recent research conducted by Tijani, Zeegers and Waele has determined that having a bulb at the end of the resonator can generate turbulence and so acoustic power losses occur (Tijani, Design 54). Instead, using Equation 7 they found that a 9° cone-shaped buffer serves the same purpose, but does not produce as much acoustic power loss. This can be made of copper or aluminum.

Swift has found that power losses are also minimized when the tube is split into large diameter and small diameter sections, where the large diameter section holds the stack and the small diameter section spans to the buffer volume. Thermal loss changes as a function of the ratio of the tube diameter. Tijani found that the optimal tube ratios are 0.54 (Tijani, Design 54).
The large diameter section, which holds the stack should have rigidity and very low thermal conductivity (Tijani, Design 51). The low thermal conductivity allows the gas parcels between the two ends of the stack to remain thermally insulated during the heat pumping process. The previous Major Qualifying Project work completed by Hilt used copper for the stack housing. This was a mistake because there was heat loss during the pumping of heat from one heat exchanger to the other, reducing Delta T. Instead this section should be made of a thermal insulator. For this section of the tube Swift proposed using fiberglass and epoxy with a metal film coating to block diffusion of the gases inside of the device (Swift, TA Engines 1168). Tijani proposed using POM-Ertacetal for this (Tijani, Design 51). It is important that the section of the tube at the heat exchanger is very thermally conductive. The small diameter section of the resonator can be made of copper or aluminum. It is important that the connection between the different sized tubes is tapered to avoid dissipation of power.
2 Design and Construction

The design for this project was initially based off of Tijani’s Design as shown in Figure 1 (Tijani, Design 2). Ideally this design would have been implemented entirely. Due to time constraints, many design aspects had to be modified.

![Figure 1- Tijani’s Design](image)

2.1 Speaker and Housing

Tijani’s design used a mechanical driver to make sound waves in the resonator. Due to time constraints, other methods were researched. The use of a common loudspeaker was chosen. A Pyle PLX32, a 3.5 inch, 100 watt, 2-way coaxial speaker was purchased to drive the thermoacoustic refrigerator. Although the possibility of using copper for the device’s speaker housing was researched, PVC was chosen as the primary material for the driver housing because it is readily available, easy to machine, and thermally insulating.
PVC piping was utilized as the primary material for the speaker housing. A 4 inch PVC slip cap and a PVC cleanout adaptor with threaded plug were bought after researching the different styles of drain piping at the local Lowe’s hardware store in Worcester. Using the acquired materials, a hole was machined into the drain cap for the speaker face. Two holes were also drilled into the PVC slip cap for the BNC and helium fittings. Once the holes were properly drilled, PVC glue was applied to secure the drain pipe within the drain cap.

In order for the speaker to fit within the speaker housing, the mounting facets on either side of the speaker were bent at 90-degree angles. The next task was to secure the speaker in a way that would prevent the speaker from moving around and make it easily removable if the speaker blew and needed to be replaced. Due to the shape of the speaker, it needed to be spaced back 0.75 inches from the hole to prevent the speaker from making contact with the speaker housing. To do this, pieces were acquired from around the lab. These included arc shaped foam fittings in conjunction with a metal halo to space the speaker. To keep the speaker secure aluminum sheeting was folded and the pieces were wedged in between the speaker perimeter and the speaker housing wall. Figure 2 shows the speaker housing components.
The speaker’s electrical wires were soldered onto the appropriate leads. Sealant tape was then applied to the threading on the PVC plug and it was then screwed into the slip cap to prevent pressure leaks.

### 2.2 Resonator

The resonator is the body of the thermoacoustic refrigerator in which the sound waves from the speaker resonate. When discussing the resonator the shell of the thermoacoustic refrigerator between the speaker housing and the buffer volume will be discussed.
Tijani’s design involves a resonator with a large diameter section and a small diameter section. The small diameter section is approximately half of that of the large diameter section. The resonator should also be structurally sound to prevent any pressure or sound loss. Use of copper for all parts of the resonator except the stack housing was planned, which would be made of a material with low thermal conductivity.

The most cost-effective and time-efficient way to construct the resonator was using plumbing supplies. The small diameter tube is a scrap piece of copper tube found in the laboratory that closely matched the desired dimensions. It had an inner diameter of 20 mm and an outer diameter of 22 mm. Instead of machining a taper to connect the small and large diameter a copper reducer that tapered from 0.75 inches to 1.5 inches was purchased. Also, to connect the small diameter tube to the buffer volume, a male copper adapter was used.

For the stack housing, the use of POM-Ertacetal, a rigid material with low thermal conductivity, was planned. After researching this material, PVC was used because POM-Ertacetal was not readily available. A PVC pipe with an inner diameter of 0.5 inches at R&R Plumbing Supply Corp. was bought. The next issue faced was connecting the copper piping to the PVC in such a way that could withstand pressures of at least two atmospheres. The possibility of using rubber O-rings in conjunction with quick-connect flanges was explored in order to create a maneuverable and interchangeable high-pressure seal. Flanges were decided not to be used after it was realized that they only came in limited sizes that did not fit our design plans. It was suggested that the copper be connected to PVC using the copper reducer, threaded adapters and PTFE thread sealant.
tape. A female copper adapter and a male PVC adapter with an inner diameter of 40.5 mm were chosen. This allowed the edge of the stack and heat exchangers to be in close thermal proximity to the outside environment.

Since heat needs to be exchanged with the environment at the other side of the stack as well, PVC needed to be converted back to copper. To do this, another threaded adapter was used on the other side of the stack. Two female copper threaded adapters were used as well. Since the speaker housing was made of PVC, the resonator should also be made of PVC so that PVC glue could be used to bond the two. For this connection, the same threaded adapter was used as those on both ends of the stack housing. Sizes that fit approximate planned dimensions were chosen.

After collecting all of the necessary parts for the resonator, it could be assembled. The small diameter tube was cut such that its length plus the length of the buffer volume threaded adapter was exactly to 20 cm. The small diameter tube was soldered to the adapter and the copper reducer. The copper reducer was then soldered to the 1.5 in copper adapter. Figure 3 shows the assembled small diameter tube after soldering.
The stack housing needed to have a total length of 85 mm. To achieve this, the 1.5 inch PVC pipe was cut to a length such that the length of both PVC adapters plus the PVC pipe was exactly 85 mm. The pieces were glued together using PVC glue. Figure 4 shows the assembled stack housing after gluing.

The next part of the resonator assembly was the section between the stack and the speaker housing. In Tijani’s design, the stack and the speaker were very close to each other. The two copper adapters were shortened as much as possible and soldered
together to closely match the design. Figure 5 shows the finished soldered copper adapters.

![Figure 5- Soldered Copper Adapters](image)

The remaining PVC adapter needed to be connected to the speaker housing. To do this, a hole matching the outer diameter of the PVC adapter was cut in the speaker housing. PVC glue was then applied to the PVC adapter and it was slid into the machined hole. Figure 6 shows the PVC adapter glued to the speaker housing.

![Figure 6- PVC Adapter and Speaker Housing](image)
2.3 Stack

Following Tijani’s design a parallel plate stack design was pursued. The parallel plate stack consists of Mylar plates that are spaced using fishing line spacers. The proposed design included Mylar plates since Mylar is known to have a low thermal conductivity.

For the final design, a spiral stack design was chosen over the parallel plate design since it was easier to obtain the necessary materials. Although it was much more time consuming, it was more realistic to produce within the project’s time frame.

After researching several different types of films Melinex was chosen over Mylar. Dupont Teijin Films was contacted about Mylar for this project and after speaking with a Dupont representative, a free roll of Melinex was generously sent. Since Melinex’s thermal conductivity and heat capacity are comparable to Mylar, the design of the spiral stack was changed to include Melinex.

Rapala 0.3 mm diameter fishing line was purchased from Target to account for the spacers between the layers of Melinex. The fishing line was secured onto the film using a Krazy glue pen.

A wooden dowel of 8.33 cm and 6.7 mm diameter was Krazy glued at the beginning of the Melinex stack to serve as a starting point for the final spiraled piece. For the first 50 cm of the Melinex sheet strips of fishing line were glued every 3.5 mm. After the first 50 cm the spacing between the fishing line strips was increased to 1.2 cm.
Throughout the entire process the fishing line was meticulously glued into place taking careful precautions that the spacing was exact and the fishing line was lying straight along the film. In order to achieve a final diameter of 40.0 mm the total length of the Melinex unrolled was 4.5 m.

Careful consideration was taken when rolling up the stack. The excess fishing line was first cut off of the film in order to ensure that the spacers were flush with the Melinex. Next the Melinex was cut to the desired width of 8.33 cm, in order to match the length of the stack housing and dowel, by accurately measuring, using calipers, and marking where to cut. Once the material was cut to the specific width, the stack was rolled into place. It was imperative that the stack be rolled tight enough that there was no extra space besides the spacing left by the fishing line between the layers of Melinex but not so tight as to compromise the fishing line spacers. Figure 7 shows the stack after being inserted into the stack housing.

Figure 7- Stack inside of stack housing
2.4 Heat Exchangers

Tijani proposed to construct the heat exchangers out of two copper sheets that had been wound together. One of the copper sheets would be flat and the other would have a sine channel structure produced by passing the copper sheet through a toothed device.

In order to construct the heat exchangers it was purposed to solder two copper sheets together at one end and then wind them around one another. Once completely rolled up the two sheets would be soldered to the external surface of the spiral. Figure 8 shows this design.

![Figure 8- Proposed heat exchanger design](image)

After extensively researching copper sheets online aluminum sheeting was chosen for the heat exchanger design. Although copper sheeting is much more thermally conductive than aluminum, aluminum was the next best option based on its availability and price.

Union aluminum rolled flashing was purchased in hopes of substituting it for the copper sheeting. However, with further analysis of Tijani’s design, it was decided to look for other alternatives due to limitations on time and the expertise in construction of such a piece.
Copper mesh as well as copper wool were discovered in the laboratory. It was decided to first test the thermoacoustic refrigerator using layers of the copper mesh of thickness 0.3 mm and wait until later trials to test the copper wool.

In order to make heat exchangers out of the copper mesh ten circles were cut out of the sheet of copper mesh. Each heat exchanger would be composed of five circles stacked together, varying in size from 4.56 to 4.81 cm, in order to ensure proper thermal contact between the stack and the heat exchangers.

To better ensure that the mesh copper disks made good thermal contact with the surroundings, the circles were placed within the piping so that they were slightly concave in relation to the stack and stack housing. The concave circles should provide appropriate thermal contact since there is a maximum amount of copper touching the stack as well as the copper piping on either side of the stack housing. Figure 9 shows the copper mesh inside of the threads of the copper adapter before being screwed onto the stack.

![Copper mesh heat exchanger](image)
2.5 Buffer Volume

The buffer volume has the purpose of simulating an open-end resonator. This could be achieved using a spherical shape or a conical shape. Tijani’s design uses a 9º aluminum cone as discussed in previous sections.

To match Tijani’s design machining a hollow cone out of an aluminum block was considered. We enrolled in machining CNC course to explore its feasibility. Machining the cone would have been much more complicated and inefficient than was first thought and therefore other possibilities were explored.

The copper bulb constructed by Hilt remained a possibility for use. It was constructed by welding two oil cans together. This bulb was not a perfect spherical shape, but did closely match one. Figure 10 shows the copper bulb.

![Figure 10- Copper Bulb](image)

The copper bulb was slightly misshapen and there was doubt as to whether it would perform well under pressure, thus other possibilities were explored. A spherical round
bottom flask often used in chemistry experiments was found in the laboratory. A way to connect the glass flask to the small diameter copper tube was needed. To do this a glass connector with Dow Corning High Vacuum Grease was slid into the flask opening on it and glued in place using Five Minute Epoxy. On the other end, a female copper adapter was glued so that it could be attached to the male copper adapter at the end of the small diameter tube. Figure 11 shows this connection.

![Figure 11- Glass Flask to Copper Connection](image)

### 2.6 Sealing

It was desired for the thermoacoustic refrigerator to hold pressures of two atmospheres or more. To do this, leak testing, tightening and sealing was conducted. As previously stated, the thermoacoustic refrigerator was primarily sealed using PVC glue and sealant tape on threaded connections.

Initial pressure testing showed that most of the major leaks were occurring at the speaker housing-resonator connection. This was because the PVC glue had so little contact area and failed. Also, there were probably imperfections in the machined hole in the speaker
housing. Initially DAP Kwik Seal Plus caulking was used to seal this. After letting it dry, it was able to hold slightly more pressure, but still leaked before 1.5 atm. Other possibilities were then explored for sealing the connection. Five Minute Epoxy was recommended for sealing. After the epoxy was applied to the problem area and air-dried, there was a leak in the threaded connection next to the speaker housing. Considering access to this part of the resonator was not needed, Five Minute Epoxy was used on this as well. JB Weld was found in the laboratory and a layer was applied to the connection at the speaker housing. Five Minute Epoxy and JB Weld were also applied to potential leak areas on the copper bulb. Figure 12 shows the speaker housing to resonator connection. The grey material is JB Weld. After extensive leak testing, the thermoacoustic refrigerator with the copper bulb and glass bulb were able to hold two atmospheres without any noticeable leaks.

![Figure 12- Speaker Housing to Resonator Connection](image)
2.7 Construction Cost

The thermoacoustic refrigerator was built using common plumbing materials. Table 1 shows the cost of each piece used to build the thermoacoustic refrigerator. Any item not listed was acquired at no price or found in the laboratory. The total price to construct the thermoacoustic refrigerator was $116.24.

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<th>Qty</th>
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<th>Price</th>
<th>Total</th>
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Table 1- TAR construction costs
3 Results

The results consist of automatic resonance testing, manual resonance testing and many types of temperature testing. Each section will discuss the procedure and results of each type of testing.

3.1 Automatic Resonance Testing

Resonance testing was done to try to determine which frequencies would work best for temperature testing. The first type that was done was automatic resonance testing, which used the frequency generator’s frequency sweep function.

3.1.1 Setup

Using a chemical stand with an arm and clamp the thermoacoustic refrigerator was oriented in an upright position. The speaker housing was considered the top of the device and the buffer volume the bottom. When referring to the top of the stack it is the edge closest to the speaker and the bottom is the edge closest to the buffer volume.

To connect the hose for the helium and the BNC cables holes were drilled into the top of the speaker housing. Two holes were drilled corresponding to the sizes of the two connections. The hole for the helium connection was drilled directly into the top of the speaker housing and the hole for the BNC cable was drilled into the side of the top of the speaker housing.
Three tanks of helium were consumed while testing the thermoacoustic refrigerator. To ensure the levels of helium were constant for each test it was necessary to leave the helium on for the entirety of each experiment.

A Stanford Research Systems -3.1 MHz Synthesized Function Generator was used to drive the speaker. The speaker was driven at frequencies ranging from 200 to 2000 Hz and at an amplitude of 10 Volts peak-to-peak in the form of sine wave.

A RCA Wireless Microphone was utilized to measure the frequency of the sound produced from the speaker. To ensure that the microphone head was placed flat against the PVC piping of the stack, a ring stand was used to hold the microphone face. The microphone was clipped onto the ring stand, which allowed a flush connection between the microphone face and stack. The microphone receiver was plugged into the computer so that the data could be analyzed.

Free software called Spectrum Laboratory was used to record and analyze the frequency and power results received by the microphone. SpecLab is a specialized spectrum analyzer and data logger with real time audio processing. It is able to calculate real-time fast Fourier transforms of the data, showing the input frequencies and the power input associated with them. Also, SpecLab has a function called Watch List and Plotter. With this function, SpecLab can determine the most powerful input frequency at a certain frequency range and plot the frequency, along with its power. This data can then be
exported and then imported by data analysis software, such as Microsoft Excel. Spectrum Laboratory is extremely customizable and is a very useful resource for frequency testing.

Since it was impossible to obtain pressure data from within the resonator, a microphone was attached to the outside of the thermoacoustic refrigerator to measure pressure variances. To experimentally determine which frequencies to conduct temperature tests automatic resonance testing was explored. This would determine if there are distinguishable patterns based on where the microphone was placed on the resonator. Additionally, it would recognize any patterns as the device switches from air to helium.

To do this, the automatic frequency sweep function on the frequency generator was used. Frequency sweeps from 200 to 2000 Hz at 10 volts peak to peak were done. It was determined not to go higher than 2000 Hz since there was very little power output for frequencies above 2000 Hz. Both air and helium were tested at 1 atm. In the helium testing the system was flushed for 20 seconds in an attempt to obtain a higher helium concentration. In all closed-system testing, the copper bulb was used as the buffer volume. The microphone was placed at the following locations:

1. Top of resonator on the helium connection
2. Top of speaker housing
3. Bottom of speaker housing
4. Top of stack
5. Middle of stack
6. Bottom of stack
7. Bottom of resonator against buffer volume

At each of these locations, three trials were performed. Using Spectrum Laboratory, the power vs. frequency graph data was exported. It was predicted that one specific frequency would arise as the resonant frequency for all points along the resonator for
each respective gas. Contrarily, there was little correlation between the data found when
the microphone was placed at different points along the resonator. A shift in peak
resonant frequencies was also expected when comparing the peaks between the air and
helium considering the speed of sound in air at 20°C is 344 m/s and in helium is 926 m/s.
Based on the ratio between the two gasses, the peak frequency in air was expected to shift
by a ratio of 926/344, or about 269%, based on Equation 8,

\[ \frac{v}{\lambda} = f, \quad (8) \]

Where v is the velocity, \( \lambda \) is the wavelength and f is the frequency.
Figure 13 shows the power-frequency data in air and helium for location 1. The x-axis shows the frequency in Hz and the y-axis shows the power in decibels. The color-coded graph below it shows y as time and varying colors as power levels. The top graphs show data for the resonator filled with air and the bottom graphs show data for the resonator filled with helium. Notice that there were peaks at 680 Hz, 400 Hz and 1770 Hz in both air and helium, rather than a noticeable shift in peaks between the two gases.

Figure 13- Microphone at the top of resonator.
Figure 14 shows a trial with the microphone at location 2 and the resonator filled with air (top) and the resonator filled with helium at 1 atm (bottom). In air there were clear peaks at 920 Hz and 540 Hz. In helium there were peaks at 470 Hz and 850 Hz. This does not match the expected shift of about 269% from air to helium.
Figure 15 shows a trial with the microphone at location 3 and the resonator filled with air (top) and the resonator filled with helium at 1 atm (bottom). In air, there were peaks at 940 Hz and 1160 Hz. In helium, there were peaks at 500 Hz and 1170 Hz. The peaks between 900 Hz and 1250 Hz in air and helium are similarly shaped, but this goes against the frequency shift expectation.
Figure 16 shows a trial with the microphone at location 4 and the resonator filled with air (top) and the resonator filled with helium at 1 atm (bottom). There was a peak in air at 1100 Hz and a peak in helium at 970 Hz.

Figure 16- Microphone at top of stack
Figure 17 shows a trial with the microphone at location 5 and the resonator filled with air (top) and the resonator filled with helium at 1 atm (bottom). In air there were peaks at 1130 Hz and 1870 Hz and in helium there was a peak at 1180 Hz.

Figure 17- Microphone at middle of stack
Figure 18 shows a trial with the microphone at location 6 and the resonator filled with air (top) and the resonator filled with helium at 1 atm (bottom). In air there was a peak at 1160 Hz and in helium there was a peak at 940 Hz.
Figure 19 shows a trial with the microphone at location 7 and the resonator filled with air (top) and the resonator filled with helium at 1 atm (bottom). In air there were peaks at 470 Hz, 890 Hz, and 1880 Hz. In helium there were peaks at 710 Hz and 320 Hz.
Figure 20 shows a trial with the microphone at the end of the resonator with the buffer volume removed from the device. There were peaks at 890 Hz and 1700 Hz. This data was clearer than the data taken with the closed resonator. This was expected because this trial was a direct measurement of the air pressure rather than the resonance of the body.

Figure 20- Microphone at bottom of open-air resonator

Figure 21 shows the cumulative percentage of the maximum for each frequency bin in the automatic resonance testing. To compute this, the power vs. frequency data in the automatic resonance testing was collected. To normalize each of the power values, each power value was chosen to be a ratio of the peak amplitude. These ratios were then summed together for each 100 Hz frequency bin. Notice that the histogram shows relatively high peak frequencies between 900 Hz and 1000 Hz that were 1.5 times more common than any other frequency bin.
3.1.2 Testing Conclusions

Automatic resonance testing provided little useful data that could be used to experimentally determine which frequencies would be best for temperature testing. It was believed that one specific frequency would arise as the resonant frequency for all points along the resonator for each respective gas. Contrarily, there was little correlation between the data found when the microphone was placed at different points along the resonator. This could have occurred because the microphone was not directly measuring the pressure at different points in the resonator, but instead was measuring the pressure differences on the resonator. There was also no clear connection between the peak frequencies and where the microphone was placed on the resonator. This might have to do with the geometric complexity as well as minor internal flaws of the resonator. It may also have to do with the unavoidable difficulty of placing the microphone in the same place for each testing location. It was possible that slight placement inaccuracies could have caused large changes in spectrum readings. In addition to these faults, there could have been difficulties pertaining to the automatic sweep setting on the function generator.
This could have happened because the setting was not outputting equal powers to each frequency in the spectrum. Also, the frequency peaks did not meet the 269% frequency shift that was expected. This could have been because the helium inside the resonator was not pure.

### 3.2 Manual Resonance Testing

The automated resonance testing provided little information as to what frequency to temperature test at. There could have been faults in the automatic sweep function so it was decided to manually test for resonant frequencies as well. To do manual resonance testing, the frequency generator was started at 200 Hz and the increase frequency button was held down so that it increased by a frequency of 1 Hz approximately every 0.3 seconds until 1800 Hz. Spectrum Laboratory has the option to record the loudest frequency present and the power reached by that frequency. The sampling rate of Spectrum Laboratory was set to 0.3 seconds per sample to match that of the increasing frequency of the frequency generator. This resulted in approximately one sample for each frequency. As a baseline, frequencies louder than -65 dB were not included.

The device was tested for air and helium at 1 atm and helium at 1.5 atm. For all helium tests, the system was flushed for 20 seconds in hopes of achieving a higher concentration of helium.
Due to time constraints, only the top and bottom of the stack were tested. It was decided these would be the best location since it was where the pressure oscillations matter most with respect to temperature change at the hot and cold exchanger.

Figure 23, Figure 23, and Figure 24 show the power outputs of frequencies recorded at the bottom of the stack with the glass bulb attached in air and helium at 1 atm, as well as helium at 1.5 atm, respectively. Any frequencies not recorded were below the -65 dB range. The two helium figures take similar shapes. Although the helium peaks do not match up, 1000 Hz at 1 atm and 1040 Hz at 1.5 atm, they were very similar and in both cases their envelopes span from 850–1260 Hz. It was possible that the internal reflections caused by the stack material, small irregularities along the inner walls, and the inaccuracy in placing the microphone in the same place along the top of the stack caused the differences in output power for the top of the stack.
Figure 22- Microphone at top of stack, glass buffer volume, air

Figure 23- Microphone at top of stack, glass buffer volume, helium at 1 atm

Figure 24- Microphone at top of stack, glass buffer volume, helium at 1.5 atm
Figure 25, Figure 26, and Figure 27 show the power outputs of frequencies recorded at the bottom of the stack with the glass bulb attached in air and helium at 1 atm, as well as helium at 1.5 atm, respectively. Although for the 1.5 atm helium Figure 27 was spotty, it still seemed that the frequency envelope can be compared to the 1 atm helium figure with similar peaks occurring in all three graphs around 1100 Hz.
Figure 25- Microphone at bottom of stack, glass buffer volume, air

Figure 26- Microphone at bottom of stack, glass buffer volume, helium at 1 atm

Figure 27- Microphone at bottom of stack, glass buffer volume, helium at 1.5 atm
Figure 28, Figure 29, and Figure 30 show the power outputs of frequencies recorded at the bottom of the stack with the copper bulb attached in air and helium at 1 atm, as well as helium at 1.5 atm, respectively. The peak results for air and helium and 1.5 atm were very similar at 830 Hz and 810 Hz the primary shape of the frequency envelope for both helium tests were the same even though they are unexpectedly shifted. This could be due to the previously mentioned imperfections of the resonator and the internal reflections from the stack. This was also the first trial with the copper bulb. The copper bulb was very crudely made and was not a perfect sphere. This could have a serious affect on the purity of the sound wave being reflected back up the resonator.
Figure 28- Microphone at top of stack, copper buffer volume, air

Figure 29- Microphone at top of stack, copper buffer volume, helium at 1 atm

Figure 30- Microphone at top of stack, copper buffer volume, helium at 1.5 atm
Figure 31, Figure 32, and Figure 33 show the power outputs of frequencies recorded at the bottom of the stack with the copper bulb attached in air and helium at 1 atm, as well as helium at 1.5 atm, respectively. All three figures depict a double peak, although the degree varies with gas and pressure.
Figure 31- Microphone at bottom of stack, copper buffer volume, air

Figure 32- Microphone at bottom of stack, copper buffer volume, helium at 1 atm

Figure 33- Microphone at bottom of stack, copper buffer volume, helium at 1.5 atm
3.2.1 Testing Conclusions

Similar to the automatic resonance testing, the experimental data was not consistent with the desired expectations. Some of the faults in this testing could have been similar to those in the automatic resonance testing. It was possible that some of the differences between the frequency measurements between the top and the bottom of the stack can be accounted for by internal reflection of the thermoacoustic refrigerator. Because the inside walls of the device were not perfectly smooth due to the fittings between the copper and PVC piping as well as the fittings along the resonator it was to be assumed that less than one hundred percent of the sound output was being transmitted throughout the entire device. Sound was actually being caught up on these small irregularities and reflected back towards the speaker.

The primary source of internal reflection was the stack and stack material. Because the stack was physically inserted within the PVC stack holder, the sound waves were being internally reflected back towards the speaker due to the Melinex, fishing line, and wooden dowel. This accounts for the large difference between the frequency measurements for the top and the bottom of the stack. Since not all of the sound produced was able to transmit along the resonator and stack material, it can be concluded that internal reflections would be source of error, thus shifting frequency peaks from the top and the bottom of the stack.
Despite error due to internal reflection useful frequency data was obtained at the stack for each gas and pressure for useful temperature testing. It was believed that the greatest frequency peaks at a certain condition represented the frequency at which the largest pressure oscillations inside of the resonator at that point occurred. Similarly, it should represent the frequency that the largest temperature oscillations occurred.

### 3.3 Temperature Testing

After obtaining frequency data for each condition, temperature testing began. Several frequencies were tested. Two types of heat exchangers were tested and an amplifier was applied to later tests.

#### 3.3.1 Setup

To measure the temperature difference between the bottom and the top of the stack, Hewlett Packard 2804A Quartz Thermometers were used. In order to initially calibrate the thermometers, Wakefield Engineering Inc. thermal compound was applied to the thermometer heads to ensure good thermal contact between the two. The quartz thermometers were then secured together with tape. To make sure that the temperature of the room was not affected by the temperature difference, strips of glass wool were taped around each thermometer leaving only the head of each exposed. The final step was to wrap the connected thermometers with layers of loose glass wool to keep out drafts and unwanted air.
Once the thermometers were calibrated to one another the temperatures difference was recorded as an absolute error. For the remainder of the project, the thermometers were set to the t1-t2 function at medium precision (up to three decimal places).

The next step was to put the thermometers in place on the thermoacoustic refrigerator. The t1 thermometer was placed at the top of the stack on the left hand side of the device and the t2 at the bottom of the stack on the right hand side. The thermal compound was again applied to guarantee good thermal contact between the thermometers and the PVC of the stack. The thermometers were first secured in place using clear tape. To ensure the connection was flush against the device, rubber bands were wrapped around a wooden dowel and the thermometer, which provided the necessary tension on the thermometers to keep them from moving off of the stack.

### 3.3.2 Ambient Temperature Changes

Temperature testing commenced with helium, however, Delta T was very inconsistent, even without a frequency being applied. The variance of the room temperature at hour intervals for five hours was then measured to determine the range that Delta T was varying. This sample showed that it varied by at least 1.008 K.

The Delta T variance was then tested after helium at 1.5 atm was added to the system. Figure 34 shows the rise in Delta T after helium was added to the thermoacoustic refrigerator. Data was taken every minute and the arrows indicate the times small leaks occurred. Notice that the Delta T was rising without sound frequencies being applied.
This made it clear that more data needed to be taken before it could be assumed the change in Delta T was due to thermoacoustic refrigeration.

The leaks in the thermoacoustic were fixed, and then the Delta T was tested under the same conditions as before: helium at 1.5 atm. Data was taken every minute for 120 minutes at which point data was taken every five minutes. Figure 35 shows the results of this testing. Notice the similar pattern that the peaks make.
Figure 35- Second trial of Delta T at 0 Hz after helium at 1.5 atm is added.

3.3.3 1072 Hz and 536 Hz Testing

It was determined that relative equilibrium had been reached and testing of the system at 1072 Hz and 10 volts peak to peak began. 1072 Hz was chosen because it was the peak frequency at the top of the stack for the 1.5 atm helium manual resonance testing. This testing was done directly after the 0 Hz testing. Figure 36 shows the results over 15 minutes. This was negligible because the temperature oscillations due to the ambient temperatures have a peak of about 0.2 K while the Delta T after 15 minutes only changed by 0.18 K.
Figure 36- Delta T at 1072 Hz in 1.5 atm helium.

The frequency was then changed to 536 Hz to see how the system reacted. 536 Hz was tested to see how doubling the wavelength might change the results. Figure 37 shows the results over 15 minutes. Again, the rise was less than the rise due to ambient temperature change.

Figure 37- Delta T at 536 Hz in 1.5 atm helium.
3.3.4 1200 Hz and 600 Hz Testing

A second trial was conducted for Delta T with helium at 1.5 atm in order to experiment with different resonant frequencies. As with before, the system was allowed to settle to room temperature before Delta T testing with the function generator began. The function generator was turned on to 1200 Hz after the system began oscillating between 1.787 K and 1.727 K after a time of 165 minutes. Once the Delta T of the resonant frequency was no longer significantly increasing, the system was tested at 600 Hz, or one half of the experimentally determined resonant frequency. Like before, when there was no longer a significant Delta T reading, the experiment was concluded.

Figure 38 shows the time it took for the system to reach an ambient temperature. Measurements of Delta T were taken as soon as the helium was added to the thermoacoustic refrigerator. To add the helium, the flush valve was left open for approximately 20 seconds to adequately cleanse the system of air without the use of a vacuum. The Delta T readings did not begin to oscillate until the experiment had been run for 52 minutes. This suggests that the natural temperature of the helium in the tank influenced the initial linear increase in Delta T. After 52 minutes, the temperature of the room became the more important influence affecting Delta T.

To be sure that the device had reached a constant temperature, measurements with the resonant frequency did not begin until the Delta T was consistent for a time period of 20 minutes.
Once the system was stable for 20 minutes the frequency generator was turned on to an inferred resonant frequency of 1200 Hz. 1200 Hz was determined to be a possible resonant frequency from the manual frequency testing. The envelopes for both the top and bottom of the stack included 1200 Hz as a maximum or close to maximum frequency when using Helium at 1.5 atm.

Figure 39 shows the Delta T over 31 minutes with the speaker being driven at 1200 Hertz. The total change in Delta T over the given time period was 0.059 K, giving an average rate of change of 0.002 K per minute. Given this rise of only 0.059K, it may not have been significant enough to consider thermoacoustic cooling. Although the results were not drastic, once the function generator was turned Delta T began to increase linearly rather than oscillating as it had been for the previous 165 minutes. The temperature oscillated by 0.2 K with no frequency applied. This suggests that there was
some effect, however insignificant it may have been. It was also possible that the power was not strong enough to produce significant results.

Figure 39- Delta T at 1200 Hz for Helium at 1.5 atm

Once the Delta T for 1200 Hz began to equilibrate at 1.820 K the second frequency was tested. Figure 40 shows the Delta T response for half of the resonant frequency, 600 Hz. The Delta T increased linearly for 37 minutes. The total change in Delta T was 0.111 K for an average of 0.003 K per minute.
Compared with the results of Delta T at 1200 Hz, the trial using the frequency of 600 Hz was more successful. The progression of Delta T was more linear and larger by 0.001 K per minute. It is possible that 600 Hz was a better choice of frequency even though 1200 Hz was the maximum within the helium envelope. When taking internal reflections within the device due to the stack material and small irregularities within the thermoacoustic refrigerators walls into account, it was possible that 600 Hz may be the better frequency choice over the stack.

Figure 41 shows the results of the total test including the rise to the ambient temperature at 0 Hz, the rise after 1200 Hz was applied and the continuous rise after 600 Hz was applied. The arrow indicates where the frequency was turned on.
3.3.5 Amplified 1200 Hz with Copper Wool Heat Exchanger

To increase the power of the function generator a Radioshack 250 Watt Amplifier was used. This increased the power driven through the speaker, which should in turn increase the temperature difference of the device.

The system was tested using helium and copper wool as the heat exchanger in place of the copper mesh disks. To remove the copper mesh disks the device was taken apart, the copper wool was inserted into the copper heat exchangers, and put back together. The quartz thermometers were rewrapped in glass wool and attached to the stack using thermal compound, rubber bands, tape, and wooden dowels. The heat exchangers were then wrapped in a layer of glass wool to keep out any drafts that would affect the data collection process.

To prevent an excess amount of air in the resonator a TRIVAC Vacuum was used. The vacuum hose was hooked up to the flushing valve at the top of the speaker housing and
the hose clip was screwed tightly onto the vacuum house over the valve. The vacuum was turned on at a very low power for a few minutes to flush the system. This ensured the gas being tested was primarily helium and not a mixture of helium and air.

After the thermoacoustic refrigerator was vacuumed, helium at 1 atm was added to the system. Once the device reached a relatively steady temperature, the amplifier and function generator were turned on at 1200 Hz as determined by previous frequency sweeps of resonant frequencies for the system. The experiment lasted for a total of 450 minutes and Delta T measurements were taken every minute.

Figure 42 depicts the Delta T of the thermoacoustic refrigerator as it stabilized to a relatively constant temperature. Measurements were taken as soon as the helium was added to the system. For the first 19 minutes there was a strictly linear increase of Delta T. For the remaining 128 minutes the Delta T oscillated, possibly reacting to the room temperature. The initial increase in Delta T may have been a direct result of the addition of helium to the device which was already at a set temperature. Notice how the Delta T oscillations eventually reached a point where the average between the peak and trough was 0.5 K.
The RadioShack 250 Watt Amplifier was turned on in conjunction with the frequency generator driving the speaker at 1200 Hz after 147 minutes. Figure 43 shows the results from this testing. There was an immediate and significant response in Delta T. Within 9 minutes, the Delta T rose above the previous Delta T maximum. For the first 112 minutes of the thermoacoustic refrigerator being on, the response Delta T increases an average of 0.038 K per minute.

After the initial 112 minutes the system began to show signs of stabilizing. It no longer was increasing linearly or at such a rapid rate. The final and maximum Delta T of the system was 5.935 K, for a normalized Delta T of 5.465 K.
Once it was determined that there was no longer a significant Delta T between measurements, the amplifier and function generator were turned off and the BNC cable was unplugged from the system. When the BNC cable was disconnected, the BNC connector was noticeably hot. This may have been cause by the heat created within the amplified speaker rather than from pressure oscillations.

As soon as the cable was unplugged the temperature began to decrease linearly at a rapid rate. For the remaining 72 minutes of the experiment the Delta T decreased a total of 3.194 K, an average of 0.043 K per minute. This further suggests that the amplifier driving the speaker at the higher power significantly impacted the Delta T results. Once the driver was unplugged the Delta T began to decrease to the starting ambient Delta T. Figure 44 shows this part of the testing.
Figure 45 illustrates this test in its entirety. The first 146 minutes were spent recording the temperature of the device as it normalized to a stable temperature. The Delta T of the system oscillated between 0.539 K and 0.473 K after 79 minutes, which represented the range for the system's constant temperature. The amplifier was turned on after the device had normalized to a constant temperature range. The amplifier and function generator were turned on at a frequency of 1200 Hz for 204 minutes during which time a significant Delta T was observed. Once the temperature reached a plateau the amplifier and function generator were turned off and the BNC cable was unplugged from the system. For the final 72 minutes the Delta T was observed to decrease back towards the stable room temperature.
Compared with previous results of the function generator alone, this was the largest Delta T observed. The increased driving power of the amplifier was able to increase the decibel level and resulting power being driven through the speaker. Also, the copper wool may have made the exchange of heat more efficient than with just the copper mesh alone. Considering both changes were implemented at the same time, it was impossible to tell which change accounted for the difference in results. It was considered that the heat created by resistance within the speaker may have also been affecting the data. Effects of heat created by the speaker were tested later.

### 3.3.6 Amplified 463 Hz and 421 Hz

After obtaining considerable results by amplifying the sound at 1200 Hz, other frequencies were tested to see how the results would change according to frequency. 463 Hz was initially chosen for testing. This was chosen because it is the theoretical quarter wavelength resonance frequency of a tube in helium with one open end that has a length
of 0.50 meter. 0.50 meter was incorrectly recorded as the thermoacoustic refrigerators resonance length. It should really be 0.55+/−0.01 meter, giving a quarter wavelength resonance of 421 Hz in helium. This was not realized until after the 463 Hz testing was initialized.

Due to lack of time, no initial temperature data was taken. The helium was turned on and allowed to stabilize. An amplified 463 Hz was then applied to the system. Figure 46 shows these results. The rise from the initial temperature was 2.474 K.

![Figure 46- Delta T at 463 Hz with amplifier in 1 atm Helium](image)

After 190 minutes, the Delta T was considered stable enough to turn the frequency off in order to see how Delta T reacted. Figure 47 shows how the Delta T reacted after the 463 Hz was turned off. There was a decrease of 0.7 K in 40 minutes.
After a considerable dropped in Delta T was noticed, the theoretical quarter wavelength resonance of 421 Hz was turned on. Data was taken every five minutes for 140 minutes. Figure 48 shows the results after the amplified 421 Hz was turned on. The Delta T increased from the 463 Hz testing was determined to be 5.421 K. At that time, the Delta T was considered constant enough to turn off the frequency and disconnect the BNC cable. When the BNC cable was disconnected, the BNC connector and the speaker housing was noticeably warm, similar to previous amplifier testing. Within 15 minutes of disconnecting the cable, the Delta T started to fall significantly.
Figure 48- Delta T at 421 Hz with amplifier in 1 atm Helium. The arrow indicates the point that the frequency was turned off.

Figure 49 shows the total data taken in this part of the testing. The amplified 421 Hz achieved the highest Delta T of all previous tests. Delta T peaked at 7.383 K. Therefore, the amplified 421 Hz achieved a total Delta T increase of 7.564 K.
3.3.7 Effect of Speaker’s Resistance Heating

It was discovered from the amplified frequency temperature testing, that the speaker was creating a noticeable amount of heat. This was likely because of the extra resistance in the speaker due to the amplifier. If there was enough heat created by the resistance in the speaker, it would result in a higher Delta T measurement and could affect the temperature testing results. It was decided that the effect of the speaker’s heat should be tested to assess the validity of the temperature testing results.

During this testing, the temperature was taken directly on the hot copper wool heat exchanger with the thermoacoustic refrigerator taken apart. The stack was not involved in this testing since the attached stack could have resulted in thermoacoustic refrigeration rather than the resistance heating that was being tested. Also, in order to provide a
baseline temperature, the ambient air temperature was taken at a location 8 cm from the opening.

For the first test the speaker was set to the same frequency and amplifier conditions that were present during the temperature testing. Although the gas used in testing was helium, air was used since the device was not sealed. The thermal conductivity of helium is 0.142 W/m K while that of air is 0.024 W/m K, so helium conducts heat almost six times as much as air. Despite this fact, because PVC has an even higher thermal conductivity of 0.18 W/m K, it was determined that most of the heat would be transported through the PVC, rather than through the gas.

Before starting testing, the thermometers sat for a few minutes to equilibrate. Figure 50 shows the Delta T taken over 30 minutes. There was no overall rise from the initial Delta T taken, but rather similar oscillations that were seen in the temperature testing.
The effect of the speaker’s resistance heating was then tested with 421 Hz, the frequency that produced the greatest temperature difference. Data was taken for 16 minutes until problems were experienced with the amplifier and speaker. At that time, the speaker could no longer be amplified. It was suspected that the speaker might have blown. Figure 51 shows the results of this testing. Delta T rose by 0.3 K 10 minutes after the speaker was turned on and rose 0.5 K more after the speaker blew, for a total rise of approximately 0.9 K in 27 minutes.

Figure 50- Effect of speaker’s resistance heating at 1200 Hz in air.
3.3.8 Testing Conclusions

Based on this testing, it was determined that effect of the speaker’s resistance heating had little impact on the initial 30 minutes of amplified frequency temperature testing. In the amplified frequency temperature testing at 1200 Hz, the Delta T rose by 1.074 K. The effect of the speaker under these conditions over 30 minutes was shown to be negligible in the speaker testing. Therefore it was believed that the initial temperature increases at 1200 Hz testing were due to thermoacoustic refrigeration.

The amplified frequency testing at 421 Hz showed an increased Delta T of 1.58 K in 25 minutes. Discounting the fact that the speaker was turned off partway through the 30 minute testing, the heating effect of the speaker was shown to be 0.58 K over 25 minutes.
Therefore, accounting for speaker resistance heating, the total Delta T over 25 minutes was 1.00 K. Due to time constraints, further testing was not done.
4 Conclusions

Without the use of the amplifier, temperature variations between the hot and cold heat exchanger were indeterminate. Because the temperature of the room and the device constantly oscillated and the Delta T of the system using the function generator alone was slightly larger than the steady state temperature the results were inconclusive.

With the addition of the amplifier there was a significant increase in Delta T compared with the background Delta T of the room and device. The amplifier increased the power produced by the function generator and allowed the speaker to reach a larger power, which in turn drove a larger Delta T.

After noticing that the BNC cable and speaker housing were getting hot with the use of the amplifier, speaker resistance heating measurements were done. It was found that the speaker’s resistance heating in the first 30 minutes was negligible and therefore it was believed that the system experienced true thermoacoustic refrigeration.

4.1 Recommendations

The speaker chosen for this experiment had a maximum power of 85 dB. In order to achieve maximum cooling power a more powerful speaker would be necessary. It is recommended that a more powerful speaker or acoustical driver is used.
Our resonator was able to hold 1.5 atm without experiencing major leaks. Giving the thermoacoustic refrigerator a higher pressure capacity would likely allow it to cool better. Also, a higher pressure capacity would help prevent wasting helium through small leaks. Therefore, it is recommended that a more pressure-resistant resonator is used for the next project.

The resonance testing done was measuring only the exterior pressure variations created by the resonator. It was believed that this method might not have been an accurate representation of the pressure inside of the resonator. It would be useful to use pressure sensors inside of the resonator to more accurately determine resonant frequencies. It is recommended that pressure sensors be used along the interior of resonator.

The temperature testing was done by measuring the temperature on the outside of the resonator. It could also be useful to have thermometers on the inside of resonator at both ends of the stack. Also, since problems were experienced dealing with the resistance heating created by the speaker, it is recommended that this be taken into account with future testing.

If greater results are seen in the future, it would be interesting to link the cold heat exchanger to a finite reservoir and link the hot heat exchanger to an infinite reservoir. As a result, a total temperature change of the finite reservoir could be measured. If larger Delta T’s are seen in future testing, it is recommended that a finite reservoir be linked to the cold heat exchanger.
The results of this project primarily measured temperature differences across the stack. If these recommendations are executed, there could be cooling of external objects, and hence create true thermoacoustic refrigeration.
5 References


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