Thermoacoustic Refrigerator
Final Design Review Report

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Abstract

In the Thermoacoustic Refrigerator Cal Poly Mechanical Engineering senior project, we designed, built, and tested a thermoacoustic refrigeration system which achieved an average temperature difference of 11.0°C. Our system consists of a resonator tube with an instrumented stack, mounted onto a base with a speaker and amplifier. An external power supply and function generator provide the power and signal to the system, and a thermocouple reader displays the temperature of the top and bottom of the stack. The system consistently achieved a significant temperature difference between the two ends of the stack in various ambient conditions, and it was quick to respond, reaching a 5-6°C difference within 2-3 minutes. Our project documents the steps to make a simple thermoacoustic system and provides a promising learning tool for the Cal Poly Mechanical Engineering Department.
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1 Introduction

This document is the Final Design Review of the Thermoacoustic Refrigerator (TAR) senior project. A thermoacoustic refrigerator uses a standing sound wave to create a temperature difference in a component, called the stack, placed near one end of the tube. The phenomenon combines concepts from vibrations, thermodynamics, and fluid mechanics. Our objective was to make a demo unit to show the phenomenon of thermoacoustics.

Since the Critical Design Review, we finished building the system and performed several tests with different stacks. We demonstrated that the system maintains a temperature difference larger than the 2°C minimum value we specified in our Scope of Work. While we originally intended to deliver a few working stacks of different materials, we have since decided to deliver only the best stack as part of our system, and the partially designed stacks as reference for any future developments.

This document explains the manufacturing and verification outcomes of our project. We provide detailed descriptions and justifications for the manufacturing processes, as well as descriptions and results of the tests proposed in Critical Design Review. Finally, we include the User Manual, Budget, Risk Assessment, and more relevant documentation in appendices. Readers curious about thermoacoustics and anyone hoping to learn more about these systems should investigate the references listed at the end of this report [1] [2].

2 Design Overview

We have designed our thermoacoustic refrigerator as simply and cheaply as possible while meeting the requirements in our scope of work in order to have a long lasting and modifiable system. The design is detailed throughout this section and in Figure 2-1.
**Figure 2-1.** Complete Verification Prototype: This figure shows our final system design. On the left is the power supply. In the middle is the actual thermoacoustic apparatus and thermocouple reader. On the right is the function generator used to drive the system.
2.1 Design Description

Our design for the thermoacoustic refrigerator consists of four subsystems: the resonator tube, the base, and the stack, and the external instrumentation (not shown in these figures). Table 2-1 divides the ballooned components in the drawing below into these subsystems. Figure 2-2 shows the top-level assembly with the subsystems ballooned and included in a bill of materials.

![Figure 2-2. Complete Assembly Drawing: CAD drawing of entire system with components labeled.]

The external components, the function generator, power supply, and thermocouple reader, are not included in the drawing because we did not design them, and we are using them as intended. The screws which join the tube and base subsystem are not included in the table or justification because of the low requirements for their strength and other properties.
<table>
<thead>
<tr>
<th>Subassembly</th>
<th>Part</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>110_TAR_Base</strong></td>
<td>111_Enclosure</td>
<td>Houses important electrical components and provides a basic structure</td>
</tr>
<tr>
<td></td>
<td>112_Tube_Support</td>
<td>Joins base and resonator subsystems and provides a seal for resonator</td>
</tr>
<tr>
<td></td>
<td>113_Banana_Jack</td>
<td>Power inlet for the system</td>
</tr>
<tr>
<td></td>
<td>114_Speaker</td>
<td>Creates soundwave in tube</td>
</tr>
<tr>
<td></td>
<td>115_BNC_Passthrough</td>
<td>Provides a pass through for the function generator signal into the enclosure</td>
</tr>
<tr>
<td></td>
<td>116_Amplifier</td>
<td>Amplifies the signal from the function generator</td>
</tr>
<tr>
<td></td>
<td>117_Tube_Sea</td>
<td>Seals tube to tube bracket preventing loss of acoustic power</td>
</tr>
<tr>
<td></td>
<td>118_Support_Seal</td>
<td>Seals tube bracket to base preventing loss of acoustic power</td>
</tr>
<tr>
<td></td>
<td>119_Speaker_Spacer</td>
<td>Spaces speaker from underside of the base to prevent damage</td>
</tr>
<tr>
<td><strong>120_TAR_Resonator</strong></td>
<td>121_Tube_Endcap</td>
<td>Seals tube end and passes temperature probe wires through</td>
</tr>
<tr>
<td></td>
<td>122_Tube</td>
<td>Main cavity for resonance to occur</td>
</tr>
<tr>
<td></td>
<td>123_Tube_End_Sea</td>
<td>Seals end of tube preventing loss of acoustic power</td>
</tr>
<tr>
<td><strong>130_TAR_Stack</strong></td>
<td>131_Stack</td>
<td>Extracts and separates thermal energy</td>
</tr>
<tr>
<td></td>
<td>132_Suction_Spacing_Rod</td>
<td>Fixes stack position along the tube</td>
</tr>
<tr>
<td></td>
<td>133_RTDF_Probe</td>
<td>Measures temperature at each end of the stack</td>
</tr>
<tr>
<td><strong>140_TAR_External</strong></td>
<td>141_RTD_Reader</td>
<td>Reads RTD probe temperatures</td>
</tr>
<tr>
<td></td>
<td>142_Function_Generator</td>
<td>Generates signal fed into system</td>
</tr>
<tr>
<td></td>
<td>143_Power_Supply</td>
<td>Provides power for amplifier</td>
</tr>
</tbody>
</table>
2.1.1 Enclosure Design Description

The enclosure subsystem provides structural support to all the components and houses some critical electronics to prevent the user from interacting with them. A schematic of the enclosure subsystem is shown in Figure 2-3.

![Figure 2-3. Enclosure Subsystem: CAD drawing of enclosure subsystem with components labeled.](image)

The main component of the enclosure subsystem is the aluminum electronics enclosure provided to the group by Hans Verleur. The enclosure contains electrical pass-throughs for power, via banana plugs, and the function generator signal, via a BNC connection. The amplifier and speaker are inside of the enclosure.

The enclosure subsystem is joined to the resonator subsystem in two places; the tube support physically joins the systems and has been designed to seal all critical surfaces and adequately support the tube. The speaker functionally joins the systems by taking the signal from the amplifier and converting it to sound. We selected the speaker to have a good response in our frequency range.
2.1.2 Resonator Design Description

The resonator tube extends from the enclosure of our system vertically and is mounted to the enclosure with our custom-manufactured tube support. A schematic of the resonator subsystem is shown in Figure 2-4.

![Figure 2-4. Resonator Subsystem: CAD drawing of resonator subsystem with components labeled.](image)

The quartz tube is the main component of the resonator system. The acoustic oscillation is confined to the tube, and the tube's length determines our system's resonant frequency. We chose a quartz tube because of its favorable acoustic properties. An O-ring was included around the end cap to prevent loss of acoustic power through pressure leakage.

The resonator subsystem is joined to the enclosure through the tube support, and it joins to the stack subsystem through the stack spacing rod, which attaches to the tube end cap.
2.1.3 Stack Design Description

The stack subsystem has two components. The main component is the stack itself which is central to the system’s function. The other is the spacing rod, which aligns the stack in the correct place. The stack for our system uses a spiral design and can be seen in Figure 2-5 below.

![Figure 2-5. Plastic Spiral Stack: Images of our completed plastic spiral stack (with a thermocouple). Notice the thin channels created between the sheets by the spiral geometry.](image)

The stack subsystem is joined to the resonator subsystem by the hollow stack spacing rod to allow the thermocouple leads to pass through. The stack is 5 inches long and made of 0.005” PETG plastic shim wound into a spiral with about 1 mm between layers. We determined these dimensions using models outlined in the textbook, *Thermoacoustics* [1].

2.1.4 External Components

There are three external components for our design. The function generator (seen on the right in Figure 2-1) creates the waveform played by the speaker, the power supply (seen on the left in Figure 2-1) provides power to the amplifier, and the thermocouple reader (on top of the base in Figure 2-1) monitors the temperatures on either end of the stack.

2.2 Design Function

The thermoacoustic refrigerator uses the function generator to create a sinusoidal function at the resonance frequency of the air in the tube. This signal is amplified and played through the speaker causing resonance in the tube and generating a temperature difference across the stack. To run the system the user needs to plug in the power supply and function generator both to mains power and to the system, and plug the thermocouple leads into the reader. Then, simply turn everything on to
the desired settings. The User Manual in Appendix A has more detailed information. It is recommended that hearing protection is worn by users if the system is louder than about 80 dB.

2.3 Design Changes Since CDR

There have been a few design changes since our Critical Design Review. Most notably, we changed the power input from wall power to a power supply. The new design has banana ports and cables to connect the amplifier (inside the box) to an external power supply. We changed to a power supply because it created a safe, low-voltage electronic system.

Another design change included adding a 3D-printed speaker spacer that moved the speaker away from the underside of the top of the box. The speakers we used were meant to be attached from behind, so without this spacer, the edge of the speaker membrane would be squished between the speaker and the underside of the box, potentially damaging the speaker. The speaker spacer protects the speaker membrane to keep it functioning long-term.

Although we originally used resistance temperature detectors (RTDs), we switched to thermocouples for the final design because of their reliability and robustness. We learned through testing that, because of our very clear results, we did not need extremely precise temperature measurement, and the type K thermocouples we used worked just fine.

3 Implementation

For the building of our thermoacoustic refrigerator, we bought off-the-shelf components, modified common components, and manufactured a few parts. We were within budget and ended up spending a total of $935.33 (see Table 3-1 and budget in Appendix C).

3.1 Procurement

We purchased most of our material through our sponsor, Dr. Peuker, from common websites like McMaster-Carr and Amazon. We also acquired a few items that Dr. Peuker already had, like thermocouples, and a few items we, as team members, already had, including the enclosure base.

We wanted to ensure our system worked before buying our own instrumentation and testing equipment, so we ran our first few tests in the vibrations lab using the lab’s power supplies and function generators. Additionally, we borrowed resistance temperature detectors (RTDs) from Dr. Glen Thorncroft to measure the temperature difference. Once we found that we were getting significant results, we ordered a power supply and function generator. Our sponsor, Dr. Steffen Peuker, provided type K thermocouples for our later testing.

Table 3-1 shows how the sponsor’s funds were used. We started with a budget of $1000 and stayed below that.
Table 3-1. Budget Summary Table. For a closer look at where we procured each part and shipping or tax costs, see the budget in Appendix C.

<table>
<thead>
<tr>
<th>Item</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Plastic Tube, 2in OD</td>
<td>$30.00</td>
</tr>
<tr>
<td>Quartz tube, 50mm OD</td>
<td>$300.00</td>
</tr>
<tr>
<td>Amplifier</td>
<td>$32.67</td>
</tr>
<tr>
<td>Speaker</td>
<td>$139.42</td>
</tr>
<tr>
<td>Stirring Straws, 5in long, 1000 count</td>
<td>$8.54</td>
</tr>
<tr>
<td>Aluminum stock, end cap, 2.25 in D round 3 in length</td>
<td>$27.27</td>
</tr>
<tr>
<td>Carbon shim steel stock, spiral stack, 6&quot; by 100&quot; roll, 0.003&quot; thick</td>
<td>$16.92</td>
</tr>
<tr>
<td>Aluminum stock, bracket, 4.75 in D round length 3.375 in</td>
<td>$49.98</td>
</tr>
<tr>
<td>BNC Passthrough</td>
<td>$26.39</td>
</tr>
<tr>
<td>Electrical Plug</td>
<td>$22.81</td>
</tr>
<tr>
<td>Panel-Mount Double Banana Jack</td>
<td>$15.24</td>
</tr>
<tr>
<td>Test Leads with Straight and 90° Banana Plugs</td>
<td>$28.06</td>
</tr>
<tr>
<td>Blue Plastic 5&quot; x 20&quot; Shim Sheet</td>
<td>$22.15</td>
</tr>
<tr>
<td>Hex nut for power plug threads</td>
<td>$8.64</td>
</tr>
<tr>
<td>Carbon shim steel stock, spiral stack, 6&quot; by 100&quot; roll, 0.003&quot; thick</td>
<td>$16.92</td>
</tr>
<tr>
<td>Blue Plastic 5&quot; x 20&quot; Shim Sheet</td>
<td>$8.86</td>
</tr>
<tr>
<td>Function Generator</td>
<td>$106.00</td>
</tr>
<tr>
<td>Power Supply</td>
<td>$50.00</td>
</tr>
<tr>
<td><strong>Total Spent</strong></td>
<td><strong>$935.33</strong></td>
</tr>
</tbody>
</table>

3.2 Manufacturing

We organized the manufacturing of our system into several key subassemblies: enclosure, resonator tube, stack, and external instrumentation. These subassemblies allowed us to divide tasks among the group and work towards milestones efficiently. We used a mixture of processes including additive manufacturing on plastic components, manual lathe on two aluminum components, and hand building on plastics and metals. We assembled the full system with hand tools and carefully repaired instrumentation wiring when appropriate.

The speaker spacer and stack spacer were both 3D printed on Rees’ Ender 3. These parts experience low loads and are not exposed on the outside of the system so 3D printing was deemed acceptable. Pictures of the CAD models and the 3D printer used can be seen below in Figure 3.1. Rees completed the additive manufacturing tasks at his apartment in San Luis Obispo.
Figure 3-1. 3D Printed Parts: This figure shows the two models of the 3D printed parts on our system, as well as the 3D printer used to fabricate them. The bottom right picture shows the finished stack spacer in use as part of the stack subassembly.

To seal the closed-closed resonator chamber, we machined critical dimensions of the end cap and tube support with tight tolerances. These connections are sealed with rubber O-rings and silicone cement. Anders and Colleen used manufacturing drawings and machined these parts, verifying their acceptance by fitting the quartz tube. An example lathe operation is pictured in Figure 3-2, along with one of the system rubber O-ring seals. The team used manual mills and lathes in the Cal Poly Aero Hangar machine shop to complete the manufacturing of these components.
We hand constructed three stacks for the system that include the plastic spiral stack as delivered, a metal spiral stack, and a plastic straw bundle stack. Knowing that these stacks offered varied geometry and material advantages, we tested each one on our verification prototype and determined that the plastic spiral stack was by far the best. Pictures of the process and results are in Figure 3-3. The team worked together to build the stacks in the Mustang 60 machine shop, using some tools like pliers from the tool crib. Shop techs advised Anders and Yashraj to use JB Weld to join the center of the steel spiral stack to a bent straw, helping to attain a tight spiral.
We also affixed temperature probes and wired the instrumentation onto the system by hand with silicone cement and tape. These operations provided opportunities for all team members to optimize the system and develop a streamlined testing operation; see Figure 3-4. We affixed instrumentation through multiple trials and iterative build sessions in Cal Poly engineering lab space: 13-107, 192-118, and 13-101.
Figure 3-4. General Manufacturing: Colleen and Yashraj work on wiring thermocouple temperature probes in the senior project lab (left). System assembly with RTDs (right). Rees coils the plastic spiral stack in the Bonderson Project Center (bottom).
3.3 Assembly

We completed the system assembly with hand tools and silicone cement. Each electronic feature inside of the enclosure system was mounted using metric M8 hex head bolts, and the CO-AX cable mount was threaded and bolted to the enclosure. Rees soldered wire between the power jack and amplifier in the Mechatronics Laboratory. We used silicone cement to hold the resonator tube in the tube support and taped or press fit the temperature probes onto the stack. Throughout testing we disassembled and reassembled the system multiple times, often working in the Bonderson Projects Center High Bay. The final assembled Verification Prototype is pictured in Figure 3-5, complete with the procured power supply and function generator.

![Figure 3-5](image1)

**Figure 3-5.** Final Manufacturing: The group works on main system assembly in the Bonderson Project center (left). The finished system assembly, complete with power supply, wiring, and function generator (right).

3.4 Software & Electronics

The electronics for our system are very simple. The amplifier requires a 12V regulated input which is supplied from an external power supply through the polarized banana jack on the outside of the system. The other connections, a BNC jack to accept the signal from the external function generator and the internal speaker wires from the amplifier to the speaker, carry the signal to drive the system. The BNC jack is wired to the amplifier’s right channel input, and the speaker is wired to the right channel output. The amplifier is set to its maximum gain value, and volume is controlled externally by changing the waveform’s amplitude on the function generator.
3.5 Lessons Learned

We learned that adding the stack in the tube creates resistance, changing the resonance of air and demanding fine tuning. Furthermore, although we expected that finding system resonance to be simple and fast, the tuning was more difficult than anticipated; computerized tuning could become an interesting project in the future.

We also learned that delivering one stack with instrumentation is far easier than multiple, due to the need to constantly rewire temperature probes and disassemble the stack subassembly. Providing one ready system will still enable a wide variety of demonstrations and experiments for the future, meeting our goals for the project.

4 Design Verification

To be sure that the system met the requirements for the sponsor, we developed a set of specifications at the beginning of the project. This section describes how those specifications were met, or how they changed through the project as we got a better understanding of what the sponsor wanted. Where needed, statistical analysis was employed to ensure compliance with the specifications.

4.1 Specifications

Earlier in this project, after talking with the sponsor and our project advisor, we set out a list of goals for the system. These specifications are presented below in Table 4-1.

Table 4-1. Engineering Specifications: list of specifications needed to meet to produce a successful product. The “Risk” column categorizes each specification by how challenging it will be to meet: High (H), Medium (M), and Low (L). The “Compliance” column shows how we will evaluate the specification: Test (T), Analysis (A), and inspection (I).

<table>
<thead>
<tr>
<th>Spec. No.</th>
<th>Description</th>
<th>Requirement Target</th>
<th>Tol.</th>
<th>Risk</th>
<th>Compliance</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Size</td>
<td>1 m x 1 m x 1.25 m</td>
<td>Max</td>
<td>M</td>
<td>I</td>
<td>Pass</td>
</tr>
<tr>
<td>2</td>
<td>Delta T</td>
<td>2°C</td>
<td>Min</td>
<td>H</td>
<td>T</td>
<td>Pass</td>
</tr>
<tr>
<td>3</td>
<td>Lifetime</td>
<td>5 Years without service</td>
<td>Min</td>
<td>M</td>
<td>A</td>
<td>Fail</td>
</tr>
<tr>
<td>4</td>
<td>Weight</td>
<td>150 lbf</td>
<td>Max</td>
<td>M</td>
<td>I</td>
<td>Pass</td>
</tr>
<tr>
<td>5</td>
<td>Cost</td>
<td>$1000</td>
<td>Max</td>
<td>H</td>
<td>A</td>
<td>Pass</td>
</tr>
<tr>
<td>6</td>
<td>Stability</td>
<td>2lbf at maximum lever arm</td>
<td>Min</td>
<td>H</td>
<td>T</td>
<td>Fail</td>
</tr>
<tr>
<td>7</td>
<td>Common materials</td>
<td>0 materials from specialized vendors</td>
<td>Max</td>
<td>L</td>
<td>I</td>
<td>Pass</td>
</tr>
<tr>
<td>8</td>
<td>Meets learning objectives</td>
<td>Meets 1 learning objective for an ME class</td>
<td>Min</td>
<td>L</td>
<td>I</td>
<td>Pass</td>
</tr>
</tbody>
</table>
Compliance with these specifications determines our success or failure on the project. Some tests, such as the temperature difference, stability, and noise level of the system require testing to confirm compliance, identified in the DVP&R in Appendix G and in the following section 4.2.

4.2 Testing and Results

We dedicated many meetings in Spring Quarter to verifying system performance. For simple inspection tests, we achieved the results listed in the Table 4-1 Results column, and detailed below.

1. Our system measures under the volume maximum at 0.30 m x .30 m x 0.61m.
2. See 4.2.1.
3. The shortest lifetime component of our system is the speaker, which has a manufacturer specified 3-year lifetime. We expect the component to last longer because it will be run at 60W rather than its max possible 90W; however, we are unable to guarantee this.
4. The system weighs around 12 pounds including instrumentation.
5. We spent a total of $935.33.
6. See 4.2.2.
7. Components were procured from McMaster-Carr, Amazon, and MTI Inc.
8. The system meets the learning objective of enabling variable user input to the system.
9. Resonance is contained and oscillation is suitably controlled for materials used.
10. See 4.2.3s.
11. We include a 1-page Quick User Guide as well as the User Manual in Appendix A.

4.2.1 Temperature Gradient Test

The most important criterion for our sponsor was to create a thermoacoustic refrigerator with statistically significant temperature difference. We devised a repeatable performance testing procedure and ran over 20 experiments with three different stacks: Cocktail Straw Bundle, Steel Spiral, and Plastic Spiral. Testing looked like what is shown in Figure 4-1.
While testing the system with the 3 stacks we manufactured, we learned a lot about our system. With the RTDs it was surprisingly difficult to securely affix temperature probes to the stack and wire them outside of the system reliably, but this improved when we moved to thermocouples. We found that the hole in the endcap had to be sealed with silicone cement to prevent leakage from the system.

Due to the experimental nature of our project, it was important to demonstrate thermoacoustic cooling clearly. We needed to reliably deliver greater than 2°C difference from the top to the bottom of the stack. We ran 12 trials with the plastic spiral stack and identical power supply and function generator settings and recorded the data shown in Figure 4-2. These trials allowed all team members to experiment with the system, and we have all obtained a greater understanding of thermoacoustics. As such, the trials also showed the project’s achievement to demonstrate thermoacoustics and educate students to learn by doing.
As demonstrated in Figure 4-2, each day had different trends with the conditions and final temperature difference value, ΔT. We had a mean temperature difference of 11.0 °C ± 4.1 °C for a 95% confidence interval, as plotted in Figure 4-2. The large standard deviation of our data is due to the significant variation of system performance across the relatively small sample of 12 trials. We computed the confidence interval based on the following equations for predicted uncertainty for a small sample. These equations were obtained through an interview with Glen Thorncroft, Ph.D, a professor at Cal Poly.

Starting with the student t equation for estimating the true mean of a sample we have the following equation:

\[ \mu = \bar{x} \pm \frac{tS}{\sqrt{n}} \]  \hspace{1cm} (4.1)

Where \( \mu \) is the population mean, \( \bar{x} \) is the sample mean, \( S \) is the sample standard deviation, \( n \) is the number of samples, and \( t \) is the student t statistic for the desired level of confidence (95%) and the number of samples. We can estimate the mean of a future set of tests by using the following equation:
\[ \bar{x} = \mu \pm \frac{tS}{\sqrt{n}} \]  
(4.2)

By replacing the unknown population mean with our previous estimate in Eq. 4.1 we can estimate the mean of a future set of tests in terms of a previous set of tests as well as sample size and standard deviation of the future set of tests.

\[ \bar{x}_2 = \left( \bar{x}_1 \pm \frac{t_1 S_1}{\sqrt{n_1}} \right) \pm \frac{t_2 S_2}{\sqrt{n_2}} \]  
(4.3)

We can use the known sample standard deviation as an estimate for the future standard deviation. This step, which seems unjustified can be numerically confirmed with Monte-Hall computations. This gives the following estimate for a future mean:

\[ \bar{x}_2 = \left( \bar{x}_1 \pm \frac{t_1 S_1}{\sqrt{n_1}} \right) \pm \frac{t_1 S_1}{\sqrt{n_2}} \]  
(4.4)

By setting the future sample size to 1, we can get a confidence interval for the next test to be performed:

\[ \bar{x} = \bar{x}_1 \pm t_1 S_1 \left( \frac{1}{n_1} + 1 \right)^{1/2} \]  
(4.5)

Performing this computation with the values for our tests yields an average of 11.0°C ± 4.1 °C.

Additionally, the system performance rose significantly at test number six and stayed higher for the remainder of the testing. However, test six was recorded on the same day as test five, and we did not measure or experience significant changes to ambient temperature, humidity, and pressure. Therefore, we attribute this increase in system performance to better sealing the end cap hole with silicone cement following run five. Before the improved seal, Yashraj felt air escaping with the system running. Reducing pressure losses likely improved the system's ability to generate a temperature difference.

Each trial was completed carefully to maximize continuity. Trials proceeded as follows:

1. Measure and record ambient conditions (temperature, pressure, humidity).
2. Measure and record the initial temperatures of both probes to correct for calibration error.
3. Confirm that the stack top and stack bottom temperature probes are stable.
4. Turn on the speaker to the resonant frequency of the system and start the timer.
5. Record top and bottom temperature data for each 15s (then 30s, then 1 min) over 14 minutes.
6. Allow the system to settle back to ambient conditions before the next trial.

Each trial, the recorded data was plotted in Excel with error bars representing the reading and measurement error. First, we calculated and plotted the recorded temperatures of stack top and stock bottom, normalized with initial conditions. Next, we calculated and plotted the temperature difference. We present both plots from run 8 as a typical run in Figure 4-3 and Figure 4-4.
Figure 4-3. Typical Run Data: Each point on the system changed temperature over time.

![Typical Run of Temperature Measured over Time](image)

**Figure 4-4.** Typical Run Data: $\Delta T$ of the system increased over time towards steady state value.

The recorded final value of this run is the average of the last 3 data points, or $12.2^\circ C$.

We present both plots here to provide the full picture of thermoacoustics and discuss key takeaways. In the plot showing both temperature points, it is noteworthy that the cold bottom of the stack approaches a steady state value quicker than the hot top of stack; we see that the lower set of data has a more gentle slope for the last few data points. Although the total $\Delta T$ is still growing for these points, the extra acoustic energy is starting to heat up all the air in the tube and the net impact is to maintain the cold point while heating up the full system.
We look forward to seeing what other students may do to advance the analysis of our system and devise suitable test procedures. For the scope of our project, the plots for each run as shown in Figure 4-4 and the performance consistency plot in Figure 4-2 demonstrate the achievement of our temperature difference criteria.

4.2.2 Tipping Test

Since the system should be robust, we performed the tipping test described in Appendix F. The initial system was revealed to be susceptible to tipping, as shown in Table 4-2.

<table>
<thead>
<tr>
<th>Pull direction</th>
<th>Tip limit measured (N)</th>
<th>Tip limit (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forwards</td>
<td>6.5</td>
<td>1.46</td>
</tr>
<tr>
<td>Left</td>
<td>5</td>
<td>1.12</td>
</tr>
<tr>
<td>Right</td>
<td>5</td>
<td>1.12</td>
</tr>
<tr>
<td>Backwards</td>
<td>3</td>
<td>0.674</td>
</tr>
</tbody>
</table>

As data suggests, we failed our tipping test. However, in our experience of dealing with the system, we have not encountered an incident where the system was at risk of breaking due to tipping (even though we moved the system around often). Therefore, we determined that our arbitrary 2 lbf minimum specification could be ignored. We recommend that future researchers design some sort of kickstand that can support the system if they find it unstable.

4.2.3 Noise Test

We also completed an evaluation of how loud the system is. We conducted the noise test by taking measurements, using the DecibleX iPhone app, of steady-state operation for the last four minutes of three runs. The average volume of the system was recorded to be 83.0 dB at 1 ft from the system. We present individual data points for the noise level in Figure 4-5. See Appendix F for the test procedure.
Our system failed the specified 80dB maximum, so noise protection should be required in prolonged exposure to the system. It is important to note that the volume of our system depends on the voltage amplitude from the function generator; it is simple to turn the power down and make the system quieter, however doing this has a significant impact on performance.

5 Discussion & Recommendations

We learned a significant amount about engineering and the design process when doing this project. Additionally, although our system performed beyond expectations, realistically, it cannot be used for any “practical” purposes. With the current design we have no way to measure heat transfer to/from the system to determine its coefficient of performance or make use of the generated temperature difference.

5.1 Discussion

During this project we completed the engineering design process: defining the problem through brainstorming ideas, prototyping, testing, and communicating our solution. At each stage, we worked as a team to come up with the best way to move forward.

We learned that manufacturing, especially non-traditional and unique manufacturing like making the stack, takes a lot of time. We had to do several iterations on each of the stacks to achieve the right size and spacing, and with each different material, there were unique challenges. For example, it was hard to create robust spacing in the plastic spiral stack; we tried to 3D print spacers on it, solder spacer on it, and punch holes to create the spacing without success. Finally, what worked was putting super glue gel into the punched holes to force them to keep their shape. This involved putting little dots of glue in hundreds of holes, a time-consuming process!
While we met the goal of creating a thermoacoustics demonstration unit, we could not make a lab unit to test different stacks. It would be interesting to have a lab that compared different stack materials or geometry, but to do this, we would need to provide an end cap and thermocouple instrumentation for each stack. Additionally, the seal between the end cap and the tube is very tight, and a user must be careful and gentle when taking the end cap and stack out of the system. It is unreasonable to expect that students do a lab experiment involving taking the end cap on and off multiple times would have the necessary care.

We would have done a few things earlier if we knew that the system would perform well, including using thermocouples from the start and buying our own power supply and function generator. While our reasons for waiting on these components made sense, we lost testing time and data to finicky RTDs and moving around with borrowed electronics. Additionally, it would be nice to have a completely integrated system with the thermocouple reader, power supply, and function generator permanently (or semi-permanently) connected to the thermoacoustic refrigerator, all set within a single enclosure.

5.2 Recommendations and Next Steps

We recommend that the system is used to demonstrate thermoacoustics by creating a temperature difference with sound. The system is relatively easy to run, simply attach power and an input signal to the amplifier in the base, plug in the thermocouples, turn the system on, and watch the temperature change. See Appendix A for more explicit details in the user manual.

Many more tests could be done with this system. First, the stacks could be modified. With the success of the plastic spiral stack, we recommend that people build and test more spiral stacks out of different materials and explore how the material affects the performance of a stack. Additionally, tests could be run on the size and position of the stack. Do different positions in the tube give different results? How about a stack half or double the size? A researcher could also run tests that change the operation of the system. How do the frequency and amplitude of the signal change the performance?

Alternatively, the prototype we provided could be modified to improve performance. The material of the tube could be changed, or multi-material tubes with strategic placement of insulating and conducting materials. Insulation around the cold side of the stack would prevent heat transfer from the environment and improve performance. Further, fluid could be forced through a “jacket” around the outside of the resonator to enable useful heat transfer.

Finally, as students are given this demonstration, the professor should notice the questions asked by the students and use the system to test any that are interesting.

Earlier in this report, we noted that the results vary significantly between days and depending on the sealing of the tube. Other correlations for system performance should be analyzed as well.
Since the ambient conditions for each trial as in Figure 4-2 could impact the performance of system, any of these conditions could be modified and more experiments run to determine their influence on performance.

6 Conclusion

We have built a working thermoacoustic refrigerator which achieves a temperature difference of 11.0°C ± 4.1°C. The system includes the thermoacoustic refrigerator unit, with one stack instrumented with thermocouples, as well as an external function generator, thermocouple reader, and power supply. While we developed a few stacks, the plastic spiral stack worked the best and is included in the delivered system. We did not achieve every initial specification and improvements could be made, mostly in terms of the physical system’s stability and unit cohesiveness. Since we did not exactly know what we wanted when designing the unit, we identified these improvements once we were testing the system. Our system is not set up to be used for anything other than demonstration purposes. We hope our project will serve as inspiration for others to design more practical thermoacoustic refrigeration systems and continue to explore this exciting phenomenon.

References


Appendices

Appendix A – User Manual

Thermoacoustic Refrigerator User Manual:

Introduction:
This demonstration unit displays the phenomena of thermoacoustics. In the system a standing sound wave in a tube containing ‘stack’ (a cylindrical component that provides buffer for the standing wave while having air channels to let the wave pass through) is utilized to generate a temperature gradient.

Safety Hazards:
Achieving resonance in the system is vital to generate the temperature gradient, which will inherently be loud. At resonance with high enough amplitude, the system can reach around 85 to 90 dB of sound intensity. Therefore, having some sort of ear protection (earplugs or earmuffs) is mandatory.

The system is vertical and contains a 24” long vertical quartz tube. Users should be careful while around the system to not knock the tube over and shatter the quartz.
Setting Up the System:

1. Make sure that the power supply and function generator are plugged in a power outlet.
2. Pass two thermocouples through the end-cap. Using the spacer provided with the stack, attach one of the thermocouples on the top surface and the other at the bottom surface of the stack. Make sure that the thermocouples are making good contact with their surfaces.
3. Carefully, put the whole subassembly (thermocouples attached to stack, through end-cap) in the tube. Make sure the end-cap is properly sealing the tube.
4. Connect the other ends of the thermocouples to the thermocouple reader (it is recommended to connect the end of the top surface thermocouple to the far left and the end of the bottom surface thermocouple to the right connection on the thermocouple reader to obtain temperature gradient on thermocouple reader that is temperature at top – temperature at the bottom. However, any orientation can enable proper temperature recording). Record the initial temperatures.
5. Connect the banana cables from the power supply and BNC cable from the function generator to appropriate connections provided on the enclosure.
6. Turn on the power supply. Make sure that the voltage value is set around 12 V and the current value is > 0.4 A.
7. Turn on the function generator. Select a sinusoidal wave with an amplitude of 500 mV peak to peak. This is our maximum recommended driving amplitude for the system. After setting the amplitude, set the frequency at 150 Hz. This is the resonance frequency for the system that was derived after tuning the system with a sound level meter.
(8) After setting these values, turn on channel 1 on the function generator. You should hear a considerably loud humming noise, indicating that the system is at resonance. Hover your hand over the hole in the end cap through which the thermocouple wires are coming out. If any air flow is felt, make sure to seal the hole completely with an adhesive (silicone cement recommended).

(9) The system is ready to be observed.

Cautions:
At the amplitude of just 500mV peak to peak, the system will be around 85 to 90dB. We suggest not to turn the amplitude higher than this value. If the system goes beyond this value and even approaches 1V peak to peak amplitude, there is a significant chance of damage to the system. Also, it goes without saying that the higher amplitude would be, the worse for people around the system as it increases the possibility of hearing damage.

For the driving frequency, we suggest to not use low frequency values (always keep the driving frequency >10 Hz). At low frequencies, the speaker inside the system tends to oscillate at high rate that can cause structural damage to the system.

Recording a Trial:
(1) Start an Excel sheet.
(2) Record ambient temperature, relative humidity, and ambient air pressure.
(3) Create 2 columns named T1 and T2. They correspond to temperatures at the top and bottom of the stack, respectively.
(4) Turn on the system and at the same time turn on a timer. Record T1 and T2 at certain time intervals (we recommend starting with 15 second intervals and then switching to 30 second and 1 minute intervals). Continue this process for at least 11 minutes (14 to 15 minutes recommended).
(5) Create 2 columns named ‘T1 Corrected’ and ‘T2 corrected’. These columns will contain temperature values that are subtracted from the initial temperatures. Create a column called delta T that calculates the difference between T1 and T2.
(6) Create 2 more columns named ‘T1 error’ and ‘T2 error’. These columns will multiply their corresponding temperature values with 0.001, square that value, add 1 to that value, and then takes square roots of that total value. This is how we obtain error in each reading of the temperature. Create another column named ‘T uncertainty’, which will root-sum-square the values of corresponding T error values. This is the overall uncertainty of each temperature reading.
(7) Plot delta T versus time. The resulting plot should display temperature gradient that increases and steadies over time.
(8) The average of delta T values for last 3 intervals is considered the overall delta T of the trial.

Troubleshooting:
(1) If the temperature gradient is negative, switch the wire connections on the thermocouple reader.
(2) If the temperature values seem to be not normal/fluctuate, make sure that the thermocouples are making good contact with the surface of the stack.
(3) If the system is struggling to create meaningful temperature gradient (>2°C), check for a leakage in the system (mostly around enclosure and end-cap).

(4) If the thermocouple reader fails to display temperature values, check the thermocouple wires.

(5) If the system fails to generate a sound wave, check the banana cables and BNC cable connections.

Maintenance:

The system was designed for minimum amount of maintenance. We recommend checking the sealing at the top of the end-cap time to time and apply silicon cement if required. For future design updates, we suggest designing more of a permanent solution for this with epoxy.
QUICK USER GUIDE

1. Turn on the thermocouple reader and attach the top thermocouple (long lead) to T1 port and bottom thermocouple (short lead) to T2 port.

2. Note the initial temperatures and observe the ambient conditions.

3. Plug banana cables into the power supply and the system, red to red, black to black. Turn on the power supply and set to 12 V.

4. Plug the BNC cable into ch1 of function generator and the system. Turn on the function generator (make sure ch1 is deselected), select sinusoidal wave, and set the frequency to 150 Hz and amplitude to 500mV peak to peak.

5. Press ch1 on the function generator and start a timer at the same time. Note down temperature changes at set time intervals. Use bigger time intervals as the trial progresses (it is recommended to start with 15 second intervals and then slowly increasing to 30 second and eventually 1 minute intervals).

6. Run the trial for (suggested) 10 minutes.
# Risk Assessment

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## 1. Operator

### 1.1 Operator

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## 3. Operator

### 3.1 Operator

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**Note:** The table above represents a risk assessment scenario specific to an operator role in a laboratory setting. The risk assessment framework includes assessment of likelihood, probability, and control measures. The developed and approved roles and responsibilities ensure a comprehensive approach to risk management.
## Appendix C – Final Project Budget

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**Appendix E – Design Verification Plan & Report (DVPR)**
Appendix F – Test Procedures

F.1 Performance Test

**Purpose:** To determine if our system meets the 2°C temperate difference specification

**Scope:** It will test how well the stacks work

**Equipment:**

- Our system
- Power supply
- Function Generator
- RTDs and RTD Reader
- Computer to record data

**Hazards:**

- Loud Noises
- Glass Breaking

**PPE Requirements:**

- Safety Glasses
- Hearing Protection

**Facility:** Cal Poly ME Vibrations Laboratory

**Procedure:** (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):

1. Turn on RTD reader and record initial values for top and bottom of stack
2. Turn on power supply, set to 12V DC with 5A current maximum
3. Plug system into power supply at banana plug mounts, monitor for noise
4. Turn on function generator, set to 280Hz sine wave, connect to the BNC cable mount. Verify that the system begins creating a tone.
5. Take a video of the RTD screen as the system attains steady state
6. Record temperature values every 1 min (and take more at steady state)
7. Turn off function generator
8. Allow temperatures to settle
9. If appropriate, rerun experiment

**Results:**
Pass criteria is a $\Delta T$ greater than 2°C. With an uncertainty of less than 50%. (E.g., with a 2°C $\Delta T$, a 1°C uncertainty). Our system fails if it doesn’t meet the criteria or experiences a catastrophic failure. We are going to run one test and take over 25 data points once steady state is reached. We have created a spreadsheet to analyze the data where we mark down the time, $T_1$ (hot temp at stack top), and $T_2$ (cold temp at stack bottom). These temperatures will be subtracted to get $\Delta T$. There are columns for the uncertainty regarding the RTD probes and the RTD readers. The uncertainty from the testing devices will be root sum squared together. Finally, we will calculate (with uncertainty) the Carnot coefficient of performance.

**Test Date(s):** April 17th, 19th, 26th, and 28th; May 3rd, 5th, 10th, 12th
**Test Results:** PASS

**Performed By:** Anders, Colleen, Rees, and Yashraj

**F.2 Stability Test**

**Purpose:** To see how stable our system is and if we need to add components to make it more stable.

**Scope:** It is testing if our system is in danger of falling over and breaking due to an accidental impact like that on a backpack.

**Equipment:**
- Our system
- Spring scale
- Flat table

**Hazards:**
- Breaking, (if the test goes very wrong)

**PPE Requirements:**
- Safety glasses

**Facility:** ME Vibrations lab, 13-103

**Procedure:** (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):
1) zero the spring scale
2) attach the spring scale to the device at the hole of the top cap
3) one engineer will gently apply a force to one side of the device at a time horizontally, increasing the force until the opposite base edge lifts off the table. Another engineer will record the force where the opposite base edge lifts off. Then the test engineer will continue to apply force until the device tips over, and catch it. The recording engineer will record the maximum force until the tipping point is achieved.

4) repeat the tip test for each horizontal direction, 3 more times. Record the minimum force required to tip the system in 4 horizontal directions.

**Acceptance:**

If the system requires less than 2lb to raise the edge or tip it, the system fails this test.

**Test Date(s):** 4/19/23

**Test Results:**

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<thead>
<tr>
<th>Pull direction</th>
<th>Tip limit measured (N)</th>
<th>Tip limit (lbf)</th>
</tr>
</thead>
<tbody>
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<td>right</td>
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<td>1.12</td>
</tr>
<tr>
<td>backwards</td>
<td>3</td>
<td>0.674</td>
</tr>
</tbody>
</table>

FAIL

**F.3 Sound Test**

**Purpose:** To see how loud our system is while operating at resonant frequency (where the system will be at its loudest) and if we need to have hearing protection to make it safer for users.

F72: Chill Vibes
**Scope:** It is testing if our system is louder than 80 dB that can cause hearing damage to users and people in surrounding area.

**Equipment:**
- Our system
- Noise intensity measuring mobile app
- Flat table

**Hazards:**
- Tube cracking (if the test goes very, very wrong), hearing damage if sound intensity >80 dB.

**PPE Requirements:**
- Safety glasses, hearing protection

**Facility:** ME Vibrations lab, 13-103

**Procedure:** (List numbered steps of how to run the test, including steps for calibration, zero/tare, baseline tests, repeat tests. Can include sketches and/or pictures):
1) Turn on the function generator.
2) Set frequency to the calculated resonance frequency of the quartz tube.
3) Drive the frequency through the system and measure the sound intensity through the mobile app.
4) Repeat the test 2 more times.

**Results:**
If the sound intensity reaches or goes beyond 80 dB, make hearing protection mandatory while the system is in use. If cracks appear in the tube, stop the frequency and plan for other material options for tube.

**Test Date(s):** 4/26/23, 5/10/23

**Test Results:** FAIL

**Performed By:** Anders
Our project adheres to the following Gantt Chart for progress on tasks and each milestone:

Enlarged menu: