# Thermoacoustic Cooling

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## ABSTRACT

Thermoacoustic cooling refers to using mechanical energy in the form of sound to transfer thermal energy. We induce a temperature gradient in a tube solely by driving sound waves into the tube. We measure the temperature gradient across a plastic stack within the tube. We aim to determine the frequency and stack position that results in the greatest temperature gradient. In doing so, we demonstrate the effect that frequency and stack position each have on the temperature gradient. The greatest temperature gradient we measure is 15.5 °C. The best frequency is the resonant frequency of our tube, and the best stack position measured from the closed end of the tube to the top of the stack is 3.3% of the tube's length. The minimum sound volume necessary to observe significant thermoacoustic effects for our setup is 108 dB.

## 1 Introduction

The existence of thermoacoustic effetcs has been known for over a century. In the late 1850s, physicist Pieter Rijke conducted an experiment in which he heated a wire mesh screen and placed it inside an open-ended pipe. When a convective heat current was applied inside the pipe, sound was produced.[1]

Other experiments were performed to understand the phenomenon of heat-driven sound waves. Sondhauss designed a narrow tube that has a bulb as a closed end and used a candle to supply heat to the bulb. He repeated this for tubes with varying bulb size and overall length. Sondhauss found that sound waves were produced and determined that the frequency was a characteristic of the tube length.[2]

Based on previous experiments, we now understand the theory behind thermoacoustic effects. Sound waves produce both pressure and displacement oscillations when driven through a medium, like air. These pressure oscillations in turn cause temperature oscillations. The easiest way to observe this effect is by using a tube and producing a standing sound wave in the tube. For standing waves, the pressure and displacement nodes are separated by a distance of $\pi/2$, meaning that the pressure anti-node corresponds with the displacement node.[3]

All tubes have a fundamental frequency, dependent on the length and if the tube is open or closed on either end. When a wave is driven through the tube, maximum oscillations will occur when the frequency of the wave is the fundamental frequency of the tube. Thermoacoustic effects can be observed in tubes with two closed ends or with one open end, and the corresponding fundamental frequencies are given by

$$f_{closed-closed} = \frac{v}{2L} \qquad\qquad f_{open-closed} = \frac{v}{4L} \tag{1}$$

where $v$ is the speed of sound in the medium inside the tube and $L$ is the tube length. This model fits with Sondhauss' experimental results, though he never sought to explain why.

In recent years, experiments have studied the opposite effect of Sondhauss' and Rijke's experiments; it is possible to produce temperature gradients using only sound. This effect is often called thermoacoustic cooling and is the focus of our experiment.

In order to observe thermoacoustic cooling, a resonant tube, a stack, a working fluid, and a driver are needed. As discussed above, the resonant tube accommodates a standing wave which results in pressure and temperature oscillations. A straight tube and standing wave are not the only means to produce this effect; traveling waves used with a looped tube also produce thermoacoustic cooling. The stack is used so that the working fluid, typically air, can pass through it while the heat from compression is trapped at the displacement node, typically at the end of the tube.[4] Without the stack, thermoacoustic cooling cannot occur. The driver is used to produce the sound waves inside the tube.

The thermoacoustic cooling cycle is shown below in Fig. 1. The plate shown in the figure is an individual piece of the stack. In the first step of the cycle, the gas parcel moves a distance of $2x_1$ while being adiabatically compressed, resulting in a temperature increase of $2T_1$. The temperature difference between the stack and the gas parcel can be described by $\delta T = 2T_1 - 2x_1 \nabla T_m$, where $\delta T$ is the temperature difference, $T_1$ is the initial temperature of the medium, $x_1$ is the initial position of the parcel, and $\nabla T_m$ represents the temperature gradient along the stack.

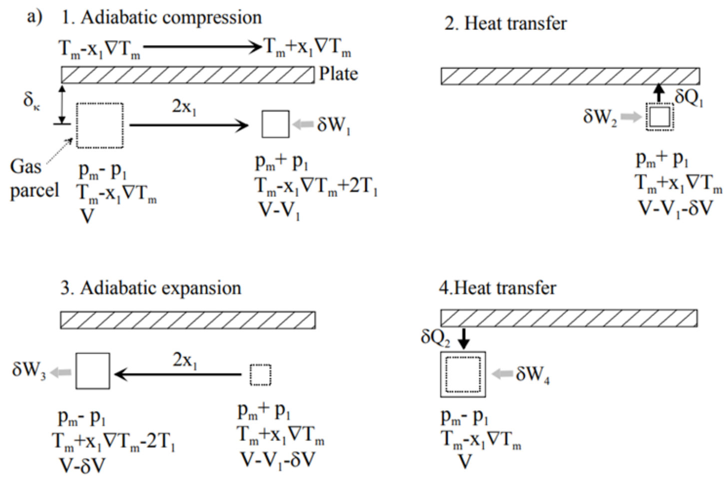


**Figure 1.** Graphic showing the thermoacoustic cooling cycle.1.) A gas parcel moves a distance $2x_1$, during which it is adiabatically compressed. This compression leads to the temperature increasing by $2T_1$. At this stage, the difference in temperature between the plate and the gas parcel can be described by $\delta T = 2T_1 - 2x_1\nabla T_m$ . The second term in this equation represents the temperature gradient along the stack. 2.) Heat is transferred at constant pressure from the gas to the plate. For positive $\delta T$ at constant pressure, heat flows from the gas parcel into the stack. 3.) The parcel moves back to its original position in an adiabatic expansion and is cooled as a result. 4.) The parcel is now cooler than the stack, so the heat flows from the stack into the gas, allowing for the cycle to start over again. As the cycle continues, heat is transferred along the stack plates through a chain-reaction such that each successive wave pulse increases the heat gradient.[5]

The second step in the cycle is a heat transfer from the gas parcel to the stack plate at a constant pressure. Heat flows into the stack for a positive $\delta T$. Next, the parcel moves back to its original position via an adiabatic expansion and is cooled as a result. Finally, heat flows from the stack into the gas parcel since the parcel is now at a lower temperature than the stack. Thus, the cycle to repeats itself in a way that increases the heat gradient with successive wave pulses. The result of this cycle is a temperature gradient along the stack with the warmer end closest to the end of the tube.

In the following sections, we will discuss our specific experimental setup, the results of our trials, and our conclusions.

## 2 Experimental Setup

Our initial experimental setup is shown in Fig. 2. We use the function generator to modulate our the frequency of our sound wave. We observe the output of the function generator with the oscilloscope to ensure the sound wave remains constant. Our resonant tube is a 60.96 cm PVC pipe with a cap on one end and the speaker on the other. We connect an amplifier to the speaker which amplifies the signal from the function generator to the speaker. We use K-type thermocouples and a thermometer to measure the temperature gradient along the stack.

We first set up the function generator to output the harmonic frequency of the PVC tube. Using Eq. 1 we calculate the fundamental frequency to be 284 Hz. To verify if this frequency is truly the resonanct frequency of our system, we cycle through frequencies on the function generator and measure the resulting loudness of sound from the tube in decibels. We find that the highest decibel rating, 108 dB, occurs when the function generator is set at 330.8 Hz.

Then, we make adjustments to the amplitude and offsets of the function generator output to ensure we are getting a clean wave on the oscilloscope. We attach the thermocouples to the top and bottom of the stack and plug them into the thermometer to measure the temperature gradient along the stack. Our stack is constructed from concentric Mylar sheets with fishing line between the sheets to ensure consistent spacing, as shown in 4. We insert the stack into the PVC at positions determined by setting the center of the stack at $\frac{\lambda}{18}$, $\frac{\lambda}{10}$, $\frac{\lambda}{11}$, $\frac{\lambda}{9}$, and $\frac{\lambda}{8}$ from the closed end of the tube. We turn on the amplifier, supplying power to the speaker to drive the sound into the tube and create a standing wave with nodes at each end of the tube. Using our thermometer and the stopwatch, we measure the temperatures at the top and bottom of the stack for 5-10 minutes. We ensure that the temperature gradient had stopped significantly changing before we end our trials.

We perform trials at 330.8 Hz with stack positions of 2 cm, 7cm, 5.9 cm, 8.1 cm, and 9.2 cm as measured from the closed end of the tube to the closest end of the stack. We also perform a trial at 248.2 Hz with a stack position of 2 cm.

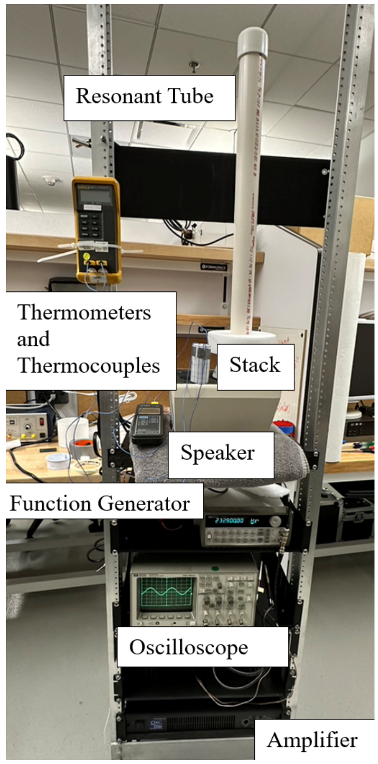


**Figure 2.** Photo of our experimental setup. The rigid PVC resonant tube accommodates a standing sound wave. The stack facilitates the formation of a temperature gradient across its two sides. The thermometer and thermocouples are used to measure the temperature at both ends of the stack. The funnel is used to bridge the diameter change from the tube to the speaker to minimize any sound loss. In later trials, we take the funnel off to create a better seal on the speaker. The function generator produces a sine wave of a given frequency which we adjust according to the resonant frequency of the tube. The amplifier outputs the signal from the function generator to the speaker, which drives the sound into the tube.

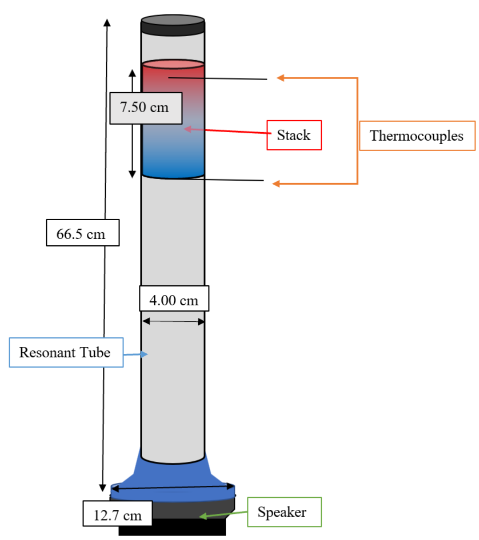


**Figure 3.** Schematic of our resonant tube system, labeled with all of the dimensions we use in our specific experiment. The stack is colored according to the expected positions of the hot and cold sides. We positioned the stack from the top of the tube based on different fractions of the harmonic wavelength.

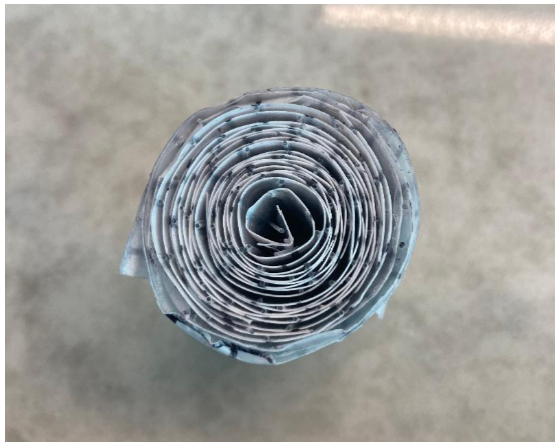

**Figure 4.** Photo showing the cross-section of our Mylar stack. This stack is constructed using thin sheets of Mylar wound in together with pieces of fishing line providing a consistent spacing.

# 3 Results

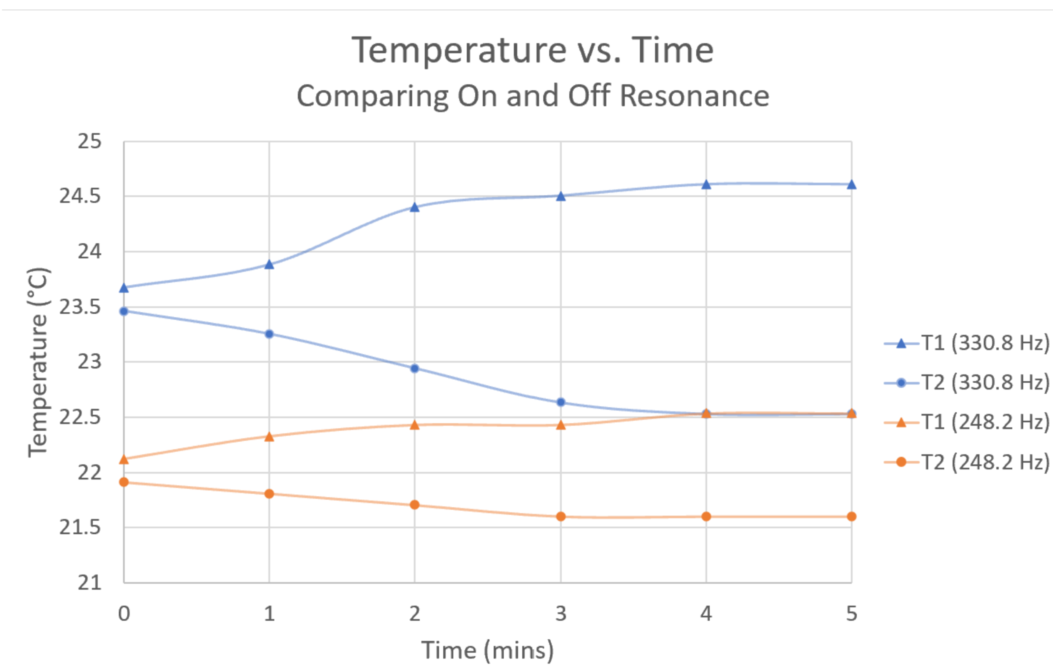


**Figure 5.** Graphs of the stack temperature versus time, showing the difference in effects between on-resonance and off-resonance. $T_1$ on the graph corresponds to the hot thermocouple, while $T_2$ corresponds to the cold thermocouple. Both trials are done with identical parameters except the frequency. The blue lines show the temperatures for on-resonance, 330.5 Hz. The orange lines show the temperatures for off-resonance, 248.2 Hz.

The results of trials with constant stack position at on and off-resonant frequencies are shown in Fig. 5. The temperature difference achieved at on-resonant frequency is 2.3 times the temperature difference for off-resonance. Using the resonant frequency increases the amplitude of the sound in our tube which produces a greater thermoacoustic effect. The pressure nodes will only align properly with the calculated stack position if we use the resonant frequency, which also causes a greater thermoacoustic effect.

Fig. 6 displays the results from trials with varying stack positions at the resonant frequency. The temperature difference increases as the top of the stack moves closer to the end of the tube. The greatest difference occurs at 2.0 cm, which is the closest we can place the stack to the node of the sound wave while allowing airflow to past the hot end of the stack.

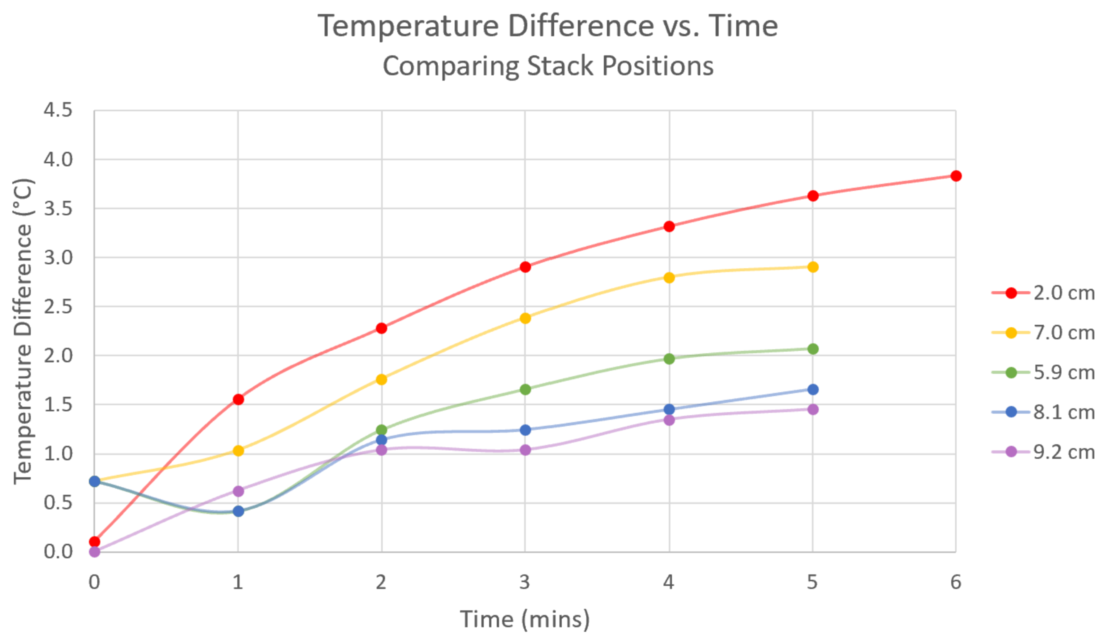


**Figure 6.** Graph of temperature difference for varying stack positions at the same frequency. The value of the positions shown on the right correspond to the distance from the closed end of the tube to the top of the stack. The distances are calculated by setting the center of the stack at $\frac{\lambda}{18}$ for 2.0 cm, $\frac{\lambda}{10}$ for 7.0 cm, $\frac{\lambda}{11}$ for 5.9 cm, $\frac{\lambda}{9}$ for 8.1 cm, and $\frac{\lambda}{8}$ for 9.2 cm.

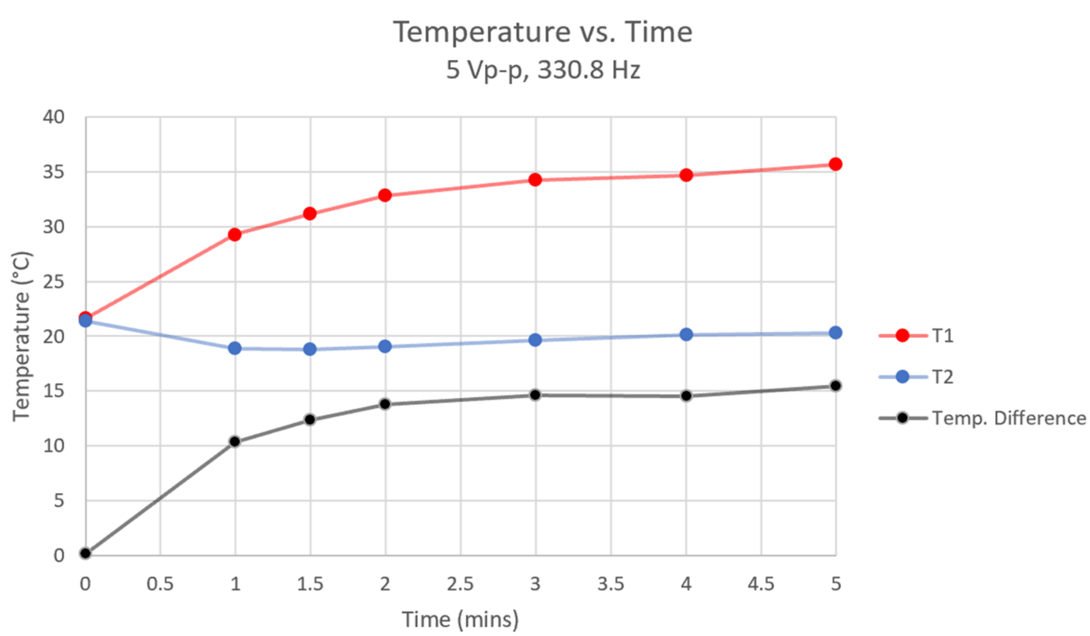


**Figure 7.** Graph showing data from our best trial. The maximum temperature difference we achieve is 15.5 °C. This occurs when the function generator is set to produce 5 $V_{p-p}$ at 330.8 Hz.

We achieved the greatest temperature difference for the results shown in 7. We use the resonant frequency, 330.8, and the optimal stack position determined by previous trials, 2.0 cm. We drive the speaker at 5 $V_{p-p}$, a 4 $V$ increase from previous trials. The increased power accounts for the greater temperature difference compared to earlier trials, since sound waves with higher amplitude produce greater thermoacoustic effects. With these optimal parameters, we measure a stable temperature difference of 15.5 °C after 5 minutes.

## 4 Conclusions

Our results conclusively indicate thermoacoustic cooling in our tube. Our best trial achieves a temperature difference of 15.5 °C when no other sources of heat are present. Off-resonance frequency as well as stack positions that do not align with pressure nodes result in less temperature difference, which is further evidence for thermoacoustic effects.

Other experiments report temperature differences greater than 15.5 °C. A greater temperature difference can be achieved with greater sound amplitude, which was not feasible for our setup because we lacked sufficient sound-proofing. Further optimizations include air-tight sealing of the tube and fine-tuning of the resonant frequency and the stack position, length, and geometry.

Thermoacoustic cooling setups like ours can be used for thermoacoustic refrigeration.[3] If a heat sink is attached to the cool end of the stack, heat can be removed from a separate system via that heat sink. In this way, we can refrigerate a secondary system using thermoacoustic cooling in our tube.

## References


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**5.** Tijani, M. Loudspeaker-driven thermo-acoustic refrigeration. (2001).