

Thermoacoustic Refrigeration

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ABSTRACT

This project examined the effectiveness of thermoacoustic refrigeration, which is the theory of using sound waves as a coolant. We studied the dynamics of sound, temperature, and the Carnot cycle, and used this knowledge to come to an understanding of thermoacoustics. We then applied this understanding to the construction of a small thermoacoustic refrigerator, which was built from inexpensive and readily available parts. The experiments showed that while thermoacoustic cooling was possible, high efficiency was beyond our reach due to materials restrictions. However, from these limitations we devised several proposals for increasing the efficiency of thermoacoustic refrigerators. A few suggestions for future work include using different materials, and changing the size and shape of the parts used. While there was no time or resources for us to conduct further research to test these suggestions, we hope our findings will encourage more research in this field.

INTRODUCTION

Refrigerators have become necessities in modern society. Most conventional refrigerators operate using a vapor compression cycle, a process which involves interaction between vapor and a refrigerant.^[1] While this method of chemical refrigeration is extremely efficient, the refrigerants used [once chlorofluorocarbons (CFCs), now hydrofluorocarbons (HFCs)] are ozone-

depleting chemicals, which is a major cause of concern.^[2]

Fortunately, an alternative method of refrigeration, thermoacoustic refrigeration, has been developed. Unlike conventional refrigerators, thermoacoustic refrigerators do not use environmentally-unfriendly refrigerants to fuel the system. Instead, they rely on the power of sound, by using sound waves to generate the work necessary to compress gases.^[3]

The most inhibiting characteristic of thermoacoustic cooling, however, is its current lack of efficiency. Our research aimed at developing a small-scale thermoacoustic model and using it to investigate the potential for increasing the efficiency of thermoacoustic cooling.

BACKGROUND RESEARCH

Thermoacoustics

The field of thermoacoustics is based upon the principle that sound waves are pressure waves. Sound waves are propagated through the air by the means of molecular collisions. These collisions create disturbances in air, resulting in constructive and destructive interference. Constructive interference creates a front of high pressure, compressing molecules, while destructive interference lowers pressure and in turn allows molecules in the air to expand. This property of sound waves is the foundation of the science behind thermoacoustic refrigerator.^[4]

Thermoacoustic refrigeration uses high-amplitude sounds to pump heat to respective

areas within the device through pressure oscillations. The wave in the thermoacoustic engine has a great amount of pressure and velocity fluctuations through the stack that the heat is given to the oscillating gas at high pressure and removed at low pressure. When it comes to the thermoacoustic pumps, the process is reversed. Steven Garrett and Greg Swift contributed a lot of work in which they found out that linear thermoacoustic models were developed to form a basic quantitative understanding. The most recent attempt at commercializing at thermoacoustic refrigerating device was by Ben and Jerry's in 2004 where they employed the researchers at Penn State to test and develop a working prototype to be unveiled at Earth day 2004.^[4]

Thermodynamics

One of the two branches that make up thermoacoustics, thermodynamics, is the study of temperature and pressure changes. Two basic thermodynamic laws are essential in explaining the process of thermoacoustic refrigeration.

The Ideal Gas Law plays an important role in explaining refrigeration cycles. The law is

$$PV = nRT$$

where P , V , n , and T are the pressure, volume, amount, and temperature of the gas, respectively, and R is the gas constant ($8.314 \times 472 \text{ m}^3 \cdot \text{Pa} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$). This law establishes that changes in pressure are directly proportional to changes in temperature. Certain thermodynamic cycles, including the Carnot cycle, function under this relationship. In these heat cycles, work is done to compress the gas, therefore increasing the temperature of the gas.

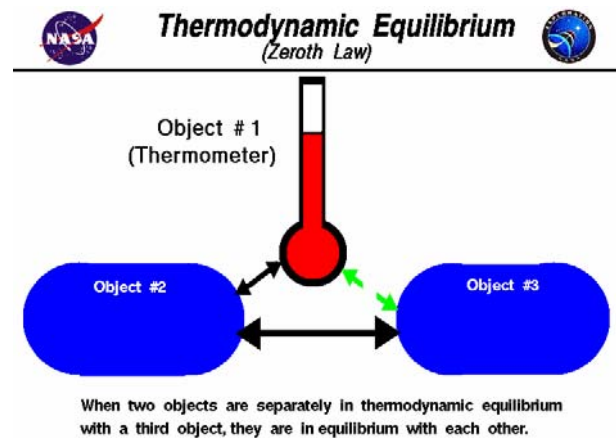


Figure 1. Zeroth law of thermodynamics.

Thermodynamics also involves another principle relevant to this experiment – the need for temperatures to reach equilibrium. The Zeroth Law (Figure 1) states that if objects are in direct contact with one another, heat will be transferred from the hotter surface to the cooler one, until both temperatures are at equilibrium.^[5]

The Carnot Cycle

The most efficient of the various thermodynamic cycles, the Carnot Cycle, as shown in Figure 2, is a reversible cycle that uses two thermal reservoirs. The Carnot Cycle is the underlying principle of all refrigeration, so it plays an important role in this project.

Four processes make up the Carnot Cycle. Two processes are adiabatic, meaning they involve the compression or expansion of gas without heat exchange outside the system. The remaining two processes are isothermal, and include a heat exchange as the gas comes in contact with a reservoir.^[6] The individual processes are explained below:

Process 1 to 2: Isothermal expansion of gas forcing piston to move. Gas expansion caused by air being in contact with hot reservoir.

Process 2 to 3: Adiabatic expansion of gas.

Temperature cools as volume increases..

Process 3 to 4: Isothermal compression of gas forcing piston to move back up the cylinder while the air is in contact with the cold reservoir.

Process 4 to 1: Adiabatic compression of gas. Temperature increases as piston forces the air to compress. This brings cycle back to the beginning.^[7]

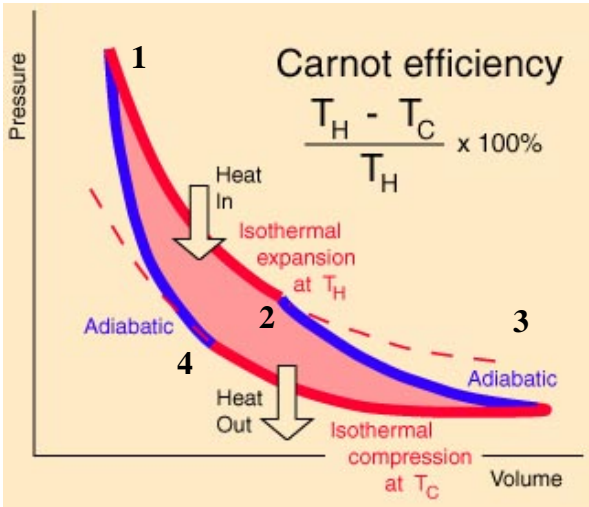


Figure 2. A P-V diagram of the carnot cycle, showing the four steps and its overall efficiency.

Sound Waves and Pressure

Thermoacoustics is dependent upon the fact that sound waves are pressure waves and are therefore able to create pressure gradients. Normally, waves do not reflect uniformly, resulting in constantly shifting gradients. However, in a thermoacoustic device the sound waves are reflected in such a way as that they become standing waves, or waves that are self sustaining and consistent. This creates a pattern of points within the device with alternating pressure maximums and velocities, as shown in Figure 3.^[8]

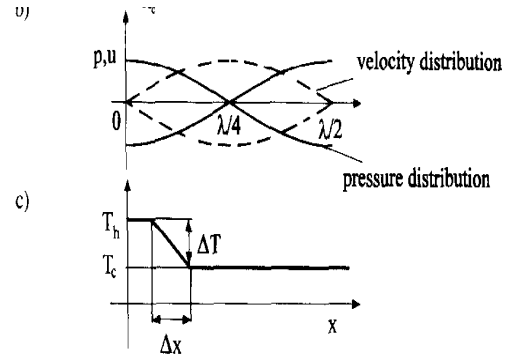


Figure 3. Graphs of sound waves. Note the relationship between pressure and velocity – as one is at its maximum, the other is at its minimum.

Although there is no net propagation of energy in standing waves, a device such as our thermoacoustic refrigerator can be constructed to take advantage of the pressure gradients. By using acoustic resonance and a stack to regulate the heat flow of the air particles, the closed tube can create regions of hot and cold in the manner of a heat pump.^[8]

Acoustic resonance occurs when the frequency of a medium's oscillations reaches that of its resonance frequency, or the point at which it vibrates naturally. At this frequency, the medium is able to absorb more energy. An added benefit is that the medium will also filter out all other frequencies, making its effect more pronounced.^[8]

In a closed tube, the resonant frequency is defined as

$$F = \frac{nV}{4L}$$

where V and L are the volume and length of the cylinder, respectively. At the point of resonant frequency, waves oscillating in the tube are at their maximum energy; by vibrating the tube at this frequency, the optimal energy flow is attained and thus the maximum heat transfer rate. To calculate this frequency, the speed of sound at a temperature T ,

$$V = 331.3 \sqrt{\left(1 + \frac{T}{273.15}\right)},$$

and the length L of the closed tube, and harmonic n (1 for this case), are used in the equation above. ^[8]

Thermoacoustic Refrigeration

In a thermoacoustic refrigerator, temperature changes are utilized through the use of a stack (a set of closely spaced filaments designed to affect heat transfer) and a metal heat sink. As a heat pump, the refrigerator takes energy from input work (in the form of sound waves) and produces a cooling effect between two regions in the tube. This occurs because the stack allows air molecules that have contracted due to the increased pressure to expand and absorb energy. ^[4]

As shown in Figure 4, molecules are first propelled by the pressure wave away from the acoustic driver (the speaker) and compressed, forcing them to release heat to the stack. As the pressure wave passes and the gas molecules are drawn back into a low pressure zone below the stack towards the speaker they again expand and attempt to draw heat back from the stack. However, it is easier for the gas to transfer heat to the stack than it is to absorb heat from the stack, so a small temperature gradient is formed. Since we use frequencies of around 385Hz, this process happens many times a second, causing a significant overall temperature gradient between the two chambers separated by the stack. ^[4]

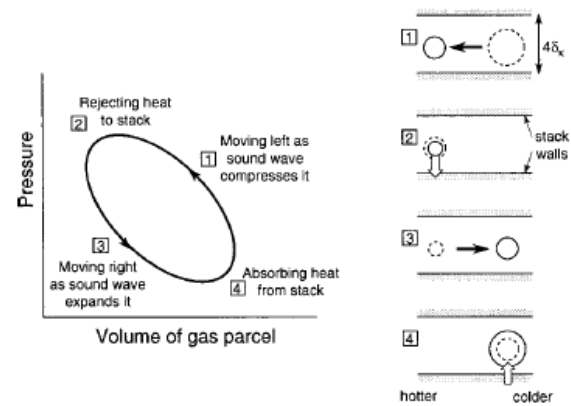


Figure 4. The thermoacoustic refrigeration cycle. On the left is a P-V diagram of the process and on the right is a cross section of the tube with exaggerated gas molecules to demonstrate the process. The speaker would be on the right side of the tube in these drawings.

Thermal Penetration Depth

One critical variable in the construction of the thermoacoustic device was the spacing between the layers of the stack. This distance is critical because it directly affects the efficiency of the device. If the space is too small, air cannot transfer the sound waves, which causes the stack to behave as a stopper. However, if the spacing is too wide, then too little air gets in contact with the stack, and not enough heat is transferred. The distance between these extremes that is most effective is described by G.W. Swift as 4 thermal penetration depths. A thermal penetration depth is the distance heat travels through air in one second. The optimal distance is four times that distance. ^[6]

Unfortunately, due to limited materials, we were restricted to a stack which included spacing of only 2.5 penetration depths. When human error is factored into stack creation, however, our inability to completely compact the stack likely left us reasonably close to the optimum 4 depths.

Critical Temperature

Another variable that must be considered while conducting this experiment

is the critical temperature of the apparatus. The critical temperature is the temperature at which heat stops transferring through the stack. The equation used to calculate the critical temperature of the stack is

$$\nabla T_{crit} = \frac{p}{\xi \rho c_p}$$

where p is the acoustic pressure, ξ is the acoustic displacement amplitude, ρ is the density of the gas, and c_p is the specific heat capacity of the gas at constant pressure.

In order for the refrigerator to function properly, the temperature difference induced by the sound wave must override the critical temperature. Heat will be transferred from the cold end of the cylinder to the warm end of the cylinder. If the temperature difference is lower than the critical temperature, the heat transfer will occur in the opposite direction, as heat moves from the warm end to the cold end. In that case, the apparatus will function as if it were a heat engine. [6]

Thermocouples

Thermocouples are widely used low cost temperature sensors that were used to measure the temperature difference between the hot and cold sections of the thermoacoustic device. [9]

Thermocouples convert thermal potential differences into electrical potential differences and rely upon the fact that metals produce voltage when subjected to a thermal gradient. This change in voltage would be negated in a circuit using the same metal; two different metals with different voltage changes must be used to produce a net voltage change. This voltage change can then be converted into a reading of temperature. [9]

Thermocouples measure the relative temperature difference between two points, not absolute temperature, so in our

experiment, the thermocouples were read using equipment that automatically referenced room temperature and translated the voltage difference on the thermocouple into an absolute temperature readout. The thermocouples we used in our experiment were type K, and were composed of chromel (nickel-chromium alloy) and alumel (Nickel-aluminum alloy) wires. [9]

RELATED WORK

Thermoacoustic technology has progressed rapidly over the last few decades due to a strong theoretical understanding of the thermoacoustic process as developed by N. Rott, J. Wheatly, and G. Swift in the 1960s, 70s, and 80s, respectively. Improvements need to be made, however, in designing refrigerators that function at higher amplitudes and in designing refrigerator components (heat stacks, etc.). In addition, thermoacoustic refrigerators need to be more efficient in order to be practical for everyday use. [2]

Research has been ongoing in this promising field of study. A few universities have carried out large scale research projects as well. Purdue University developed a model of a thermoacoustic heat pump. [13] Studies conducted at Johns Hopkins University revealed that in thermoacoustic refrigeration, maximum cooling did not correlate with maximum efficiency. [11] Out of all the universities, Penn State has done the most outstanding research in this field. It has designed various forms of thermoacoustic refrigerators, one of its most exceptional innovations being a thermoacoustic chiller that was used to cool shipboard electronics. [12]

One of the most recent experiments in thermoacoustic refrigeration was done through a highly publicized partnership between Ben and Jerry's and Penn State. Ben and Jerry's wanted to design a more

environmentally friendly refrigeration process, so they enlisted a team from the college to engineer a thermoacoustic cooling unit which was unveiled on Earth Day 2004. The Penn State team recognized that since the basic mechanics behind thermoacoustics are already well understood, research should focus on optimizing the method so that thermoacoustic coolers can compete with commercial refrigerators. After analyzing their results, the team listed the four main components of the refrigerator which they considered to be critical to optimization. These components included: the thermoacoustic core, resonance tube, heat exchangers, and acoustic driver. It was determined that the refrigerator's performance was limited by the heat pumping capacity of the thermoacoustic core, and after calculating this performance researchers showed that it was capable of cooling to the same level as traditional refrigerators.^[3]

EXPERIMENTAL DESIGN

Device Construction

In the construction of our thermoacoustic devices, we followed the methods of Russell et al^[8]. Our materials included a boxed loudspeaker, a Plexiglas tube, an aluminum stopper, film, and 15lb nylon fishing line.

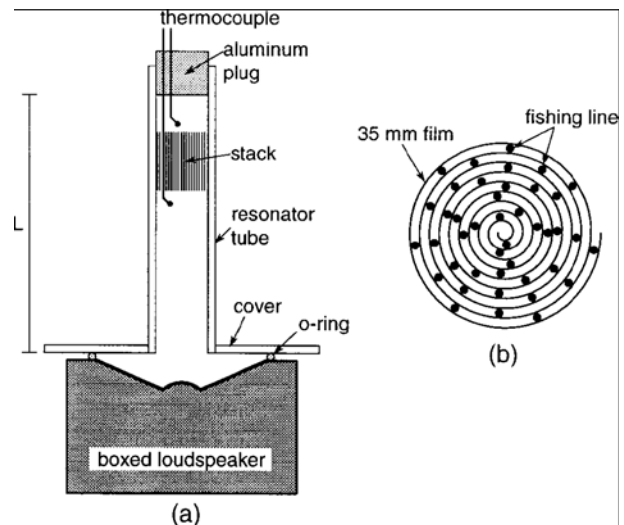


Figure 5. A diagram of the thermoacoustic device we constructed. A cross section of the stack, a roll of material interlaced with spacers, is shown on the right and a cross section of the entire device is shown on the left. The thermocouples were inserted above and below the stack.

Stack

A lot of time was spent making the most important feature of the device, the stack. It was created by gluing fishing line at evenly spaced intervals along the roll of film. To do this, we wound fishing line around a 1 meter long cardboard loom with slits cut every 5mm along the edges. After the line was wound, a meter of photographic film was secured to a stable surface and then sprayed with adhesive. The loom and line were then pressed onto the film, weighted, and allowed to dry overnight. Once dry, the cardboard and excess fishing line was removed.

The film was rolled compactly and placed inside a Plexiglass tube with a diameter of $\frac{3}{4}$ cm and a length of 23 cm. The stack was placed approximately 5 cm from the open end of the tube. Small holes were then drilled above and below the stack to serve as entry points for the thermocouples.

Thermocouples

To construct the thermocouples, a high power small scale welder was used to flash-melt the chromel and alumel wires together on one end, while other ends were connected to a K tap connector. The welded ends were then inserted into the previously drilled holes.

Adhesives and Sealant

Another Plexiglas plate was cut so that it would cover the speaker entirely. A hole was drilled in the center of this plate in order to allow the placement of the tube. To secure an airtight seal between the tube and the plate, an epoxy was used, while a silicone caulk was used on all the other areas which had potential for leakage (connection of plate to loudspeaker, thermocouple holes).

Heat Sink

Lastly, an aluminum plug, which served as a heat sink, was placed in the top end of the tube and the device was ready for testing.

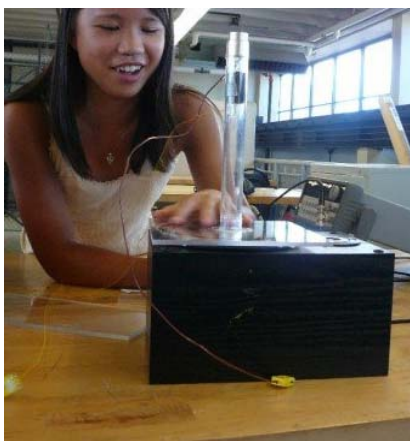


Figure 6. One of the three thermoacoustic refrigerators that was constructed.

Efficiency Testing

To test our thermoacoustic devices we set up an amplifier, a wave generator, and a multimeter to read the thermocouples. The wave generator was used to adjust the

frequency while the amplifier was used to adjust the power output of the speaker. On our first attempts the frequency was set to Russell's suggested value of 385Hz, and the power output was increased until the second harmonic became barely audible. The device was allowed to operate for several minutes while the values of the thermocouples were monitored. After each attempt, the device was allowed to return to equilibrium, after which the test was repeated, with the frequency changing each time, until we were satisfied that our refrigerators were functioning at their full potential. We focused most of our efforts on adjusting the frequency, and after numerous trials concluded that the optimum frequency for our device was 394 Hz. We then concluded our experiment by running the refrigerator at this frequency for a protracted period of time, which yielded our final results.

In order to ensure that the data gathered was constant, three thermoacoustic refrigerators were built. All three were put through the same process, and three sets of data were gathered.

RESULTS

After the thermoacoustic refrigerators were successfully constructed, they were tested for their effectiveness. After finding the optimal frequency, refrigerators were operated at that frequency over a nine minute period. Trial-and-error tests revealed that the optimal frequency for all three refrigerators was 394 Hz. At thirty-second intervals, temperatures of the upper and lower thermocouples were recorded and graphed, as shown in Figure 7 below.

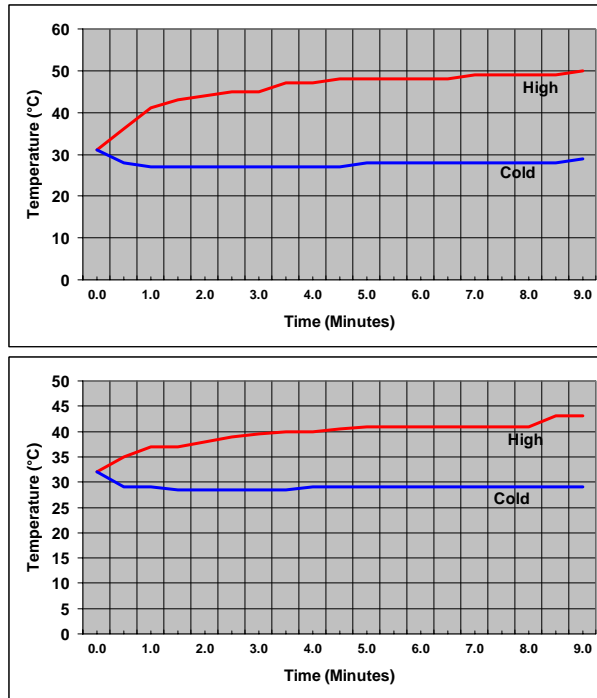


Figure 7. Temperature variation above and below the stack as a function of time. The top red line indicates the readings of the upper thermocouple, while the bottom blue line indicates the readings of the lower thermocouple.

For the tests performed on all three refrigerators, the temperature discrepancy between the hot end and cold end of the resonator tube rapidly increased for the first thirty seconds. It attained its final value after approximately three minutes. The first two refrigerators exhibited a temperature difference of 11°C and 18°C after three minutes.

Due to mechanical flaws, the third refrigerator did not yield accurate results. The thermocouples on the refrigerator were malfunctioning, and the apparatus was not sealed properly. The data collected from this refrigerator was superfluous and thus discarded.

FUTURE WORK

The use of inexpensive, household items to construct the refrigerators could explain such low efficiency. If other materials were used, it is possible that the

efficiency of the refrigerators would have improved. The heat sink could have been made out of a more conductive material, such as gold, copper, or silver. Also, the shape of the heat sink could be changed in order to increase its surface area, which would raise its thermal transfer rate from the hot reservoir to the environment. A relatively easy method of affecting this change would be to simply machine a standard computer heatsink to fit into the resonator tube. These conductivity enhancements would remove heat from the top 'hot' reservoir of the device which would facilitate an easier transfer of thermal energy from the cold reservoir to the hot.

While the thermal conductivity of the hot reservoir should be increased, the thermal conductivity of the cold reservoir should be decreased. To achieve this, the resonator tube could be constructed of a more thermally isolating material, or could be insulated using conventional external insulation techniques.

The most important part of the thermoacoustic device, the stack, could also be adjusted in several ways to increase efficiency. First, and most simply, the space between layers of the stack could be increased to the recommended 4 thermal penetration depths. The materials that the stack is composed of also have a great effect on performance. In our project we used photographic film, but if a more thermally conductive material, such as copper or gold, were used the process could be more efficient. Also, it may be worthwhile to explore the use of heterogeneous stacks, or stacks made up of several different materials. If the stack were more thermally conductive in the region where the air is most compressed and less thermally conductive where the pressure is lower, the heat transfer effect would be greatly accelerated. Lastly, the position of the stack within the resonator tube is a very important

factor that could be adjusted for optimization. The stack works best when it is centered on a region in the tube where the standing wave produces the highest pressure (and thermal) forces. Experimenting with different frequencies and stack placements could yield greater efficiency.

We also concluded that the shape and length of the resonator tube was a major factor in the efficiency of the device. Improvements to the resonator tube would involve further research into the effects that differently shaped tubes would have on the thermoacoustic effect. Perhaps a resonator tube which was tapered to focus the intensity of the wave and therefore increase both the pressure and temperature maximum would increase effectiveness. However, as stated above further research is required to ascertain the resonator tube shape of maximum efficiency. Other tube factors that should be explored include tube diameter and length. Due to the correlation between the resonator tube and the frequency used these two factors would have to be experimented with simultaneously. If peak efficiency was to be achieved, the most optimal solution would be to model the acoustic properties by computer simulation and predict efficient tube-frequency combinations in that manner.

A relatively simple modification that could be made to our models to increase efficiency would be to enclose the entire speaker in a Plexiglas box, therefore ensuring that all of the acoustic energy is directed upwards into the resonator tube. In our current models, a large percent of the energy is lost as sound that escapes the device.

Lastly, as temperature sensors for this particular application thermocouples were not the optimal choice. The type K thermocouples that were used were inaccurate below a degree Celsius within the range of 0-100, which was exactly the range

we were operating in. More practical and reliable temperature sensors, such as thermistors, should be used in the future.

CONCLUSION

We set out upon this project with the simple goal of constructing a cheap, demonstrative model of a thermoacoustic refrigerator. To this end we succeeded: this experiment proved that thermoacoustic refrigerators indeed work. Additionally, this experiment did yield some discoveries regarding the efficiency of thermoacoustic refrigeration. It was revealed that finding the optimal frequency is essential for the maximization of efficiency. This optimal frequency was found using trial-and-error, because the equation used to calculate frequency was ineffective. Another factor that increased efficiency was the proper sealing of the apparatus. If the parts are not properly sealed, heat escapes from the refrigerator, and it does not function as well. However, the overall efficiency of such an apparatus is debatable. The devices used in the experiment were capable of cooling air, but only cooled the air a few degrees Celsius. Also, the refrigerators were only able to cool the air for a short amount of time before the cooled air started rising in temperature.

Our research shows that thermoacoustic refrigeration has the potential to replace conventional refrigeration. In addition to the lack of toxic refrigerants, thermoacoustic refrigeration also requires less maintenance and is less expensive, because there are few, if any, moving parts, and most of the components can be produced inexpensively.^[3] We proved this by achieving a cooling effect, if only slight, using only household materials.

Thermoacoustic refrigeration also has a broad range of applications, including computers and nanotechnology. It will likely be employed by the military and space

program, due to its low-maintenance, toxin-free, high-reliability cooling methods.^[3]

ACKNOWLEDGEMENTS

We would like to thank the following people and organizations for making this project possible:

- Dr. Hao Lin , advisor
- Dr. Steven Tse, advisor
- Dr. Geliang Sun
- Venkat Narayanan, Graduate Student
- Jimbo Li, Graduate Student
- Megan E. Smith, Graduate Student
- NJ Governor's School of Engineering and Technology
- Rutgers University
- Blase Ur, head coordinator of NJGSET
- Eric Koo, counselor
- All other NJGSET counselors and staff

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