Recycling and Reuse Technology Transfer Center

Thermoacoustic Refrigeration

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THERMOACOUSTIC REFRIGERATION

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ABSTRACT

Thermoacoustic refrigeration, cooling by using sound, is a concept that most people have not thought of, or even heard of. It is a very simple concept, yet may take the place of conventional refrigeration which uses CFC's that are thought to damage the ozone layer. A prototype acoustic refrigerator was built with a resonant tube length of 53-cm and operating at 345-Hz with air. One of the acoustic refrigerator's main components is the thermoacoustic stack. The optimal stack length is around 9-cm for a 53-cm resonant tube. It achieved a Coefficient of Performance (heat pumped/power input) of 0.25. This was all done with an inexpensive model costing about $70 total.

NOMENCLATURE

A = Fraction of acoustic power that returns every oscillation
c = Speed of sound
C = Specific heat
D = Thermal boundary layer thickness
f = Frequency
m = Mass
p = Sound level pressure
P_T = Total acoustic power
P_D = Delivered acoustic power
P_H = Heat pumping power
r = Radius of the tube
R = Peak-to-Dip ratio of resonances of transfer impedance
T = Temperature (ΔT is change in Temperature)
t = Time
ρ = Density

INTRODUCTION

The idea of acoustic refrigeration is a fairly new idea, but the research is advancing quickly. Acoustic refrigeration works on the idea that when air is compressed, it heats up, and when it expands, it cools down. In a resonant tube driven by sound at one end, there is an oscillating flow of air in the tube. As the air rushes towards one end, it is compressed, and thus heats up. As the air starts away from that end, it expands and cools off. This cycle happens over and over, which sets up the potential for heating and/or cooling of the system. Acoustic refrigeration is attractive because it eliminates the need for CFC's, on which conventional refrigeration units rely. Another strong point of the acoustic refrigerator is that it is a very simple apparatus.

The refrigerator has few moving parts. It consists of a resonant tube, a driver, heat exchangers, and a thermoacoustic stack. The driver produces the air flow that is needed for the compression and expansion, and is the only moving part. The exchanger has to be made of a heat conducting material, so heat can be exchanged in and out of the tube in a controlled manner. The stack consists of many narrow channels in the direction of the air flow, and these allow air molecules to pass from one end to the other, which is essential for the transfer of energy. The stack is made of a non-conductive, non-porous material. The stack should not conduct heat from one end to the other because the refrigerator is based on the ability to build up a temperature difference between the stack's two ends.

A simple refrigerator can be built using inexpensive materials that can be purchased at the local hardware store, or in a junk yard. This model can then be used as a demonstration model for college and high school classes. It is very easy to build, so even a high school class would be able to build one, and they could then see first hand the process of thermoacoustic refrigeration.

Many factors affect the performance of the refrigerator. This project studied several of these factors including the length of the stack and the heat transfer through the walls of the tube. We also studied the effect of different gaseous media. The energy performance of the refrigerator was found and compared to other models being built [1]. Finally, a model was designed and built that is cheap, and easy to construct. This would allow a high school class to be able to build one.

DESIGN

Many experimental models of thermoacoustic refrigerators are being designed and tested [1]. The models that were built for this project were very inexpensive. Both models, figs. 1-2, were built for $150 or less. The model illustrated in figure 2 was used for most of the experiments. Both models rely on a resonant tube made from 4-inch (id), thick walled, PVC pipe. Figure 1 uses an 8-ohm, 75-watt, heavy duty driver. The driver was attached to the tube using a custom built connection. Figure 2 is referred to as the high school model, since it is inexpensive to build, about $70, and can possibly be built by high schoolers. The high school model relies on a 4-inch, 40-watt Zalytron speaker as a driver (other types of speakers can be used). The tube is then held together using 15-cm square aluminum plates at both ends, with threaded rods connecting them. The seams of the tube are sealed using windshield ribbon sealant. When pressure is exerted on the tube from the end plates by tightening the nuts on the threaded rods, a good seal is formed. The heat exchanger for the high school model is a section of air conditioning coil from an automobile. Figure 1 does not have a heat exchanging system, so that must be taken into account when viewing the results obtained by that model.

The key to the operation of the thermoacoustic refrigerator is the thermoacoustic stack. The stack should allow air to flow through it, but should not allow the heat built up by the compression of the air to transfer back into the cooled region of the tube. Thus, the stack should be made from a non-conductive material. The first stacks that were used were built from

Carnival Drinking Stirs (small straws), with 2-mm diameters. The stirs were cut to the desired length, and then taped together and coiled into a 4-inch diameter stack so it would fit into the resonant tube. Since this stack is easily built, many different lengths of stacks were built. The next design for the stack is closer to that used by Steven Garrett and others at the Naval Postgraduate School in Monterey, California. They use a stack that was made from a strip of plastic, with fishing line as spacers, rolled into a coil [2]. The stack used for our high school model consists of Lexan plastic cut into 9-cm. wide strips. Strips of Painters Caulk were placed about 10-mm apart to act as spacers for the stack. The strips of Lexan plastic were then coiled into a 4-inch diameter stack. The surface-to-surface spacing of the stack is about 1-mm. This corresponds to a thickness of about 8 thermal boundary layers. A thermal boundary layer is a distance that heat can be transferred to a surface in the time of a passing sound wave. This is calculated [3] by:

$$D \simeq 0.25(1/\sqrt{f})\ \text{cm} \qquad (1)$$

where f equals the frequency at which the resonant tube was run at. In this case, it was about 345-Hz.

Another important part of the acoustic refrigerator is the heat exchanger. Heat exchangers are used to transfer the heat built up on the hot end of the stack out of the unit. This allows heat to keep being transferred to that region from the cold end of the stack, so that the cold side of the stack can cool down even more, since the stack relies on a temperature difference. If the hot side is not cooled down, heat builds up, and this limits the minimum temperature achieved at the cold end. A heat exchanger can also be placed at the cold end of the stack. This allows a fluid to transfer heat into the refrigerator, so after the fluid passes through the exchanger, it has cooled down. This fluid can then be used to cool another region.

The heat exchanger in the high school model is a section of air conditioning coil from an automobile. The tubes of the coil extend to the outside of the PVC tube so fluid can be run through them. The cooling system is composed of two 5-gallon buckets. The bucket above the refrigerator is equipped with a valve at the bottom so water will flow out of the bucket, through the heat exchanger, and then into the bottom bucket. There is a bilge pump that pumps the water back into the upper bucket.

Since the acoustic refrigerator works on pressure differences, a large amount of oscillatory acoustic pressure is desirable. The drivers are powered by a 100-watt amplifier, and a Wavetek 2MHz sweep/function generator. The resonant tube is about 53-cm in length, and is run at about 345-Hz by the Wavetek generator. With the 75-watt speaker, in Model 1, the pressure level inside the tube was about 163 dB Sound Level Pressure, (SPL). The 40-watt speaker was able to obtain 153 dB SPL of acoustic pressure. The pressure levels were measured by drilling a hole into the end of the resonant tubes, and then placing a sound level meter into the hole. The pressure level was then measured directly. The sound wave is close to a sine wave, but with the distortions caused by the speakers, the sound wave was not a perfect sine wave. There were some noticeable harmonics in the sound (1st, 2nd, and 3rd especially). The harmonics were picked up by placing a microphone at the end of the tube and then the microphone was connected to a spectrum analyzer. The spectrum analyzer showed the different harmonics produced by the speakers.

The data that were most important were the temperatures. The temperatures in the refrigerator were monitored using copper-constantan thermocouples with a known reference temperature. These were placed throughout the tube when temperature measurements were being taken. The temperatures were then recorded from an OMEGA microprocessor thermometer, or by a Campbell Scientific 21X Datalogger. The Datalogger was used to collect the temperatures over time, and then the temperatures were downloaded onto a computer to be analyzed. With the Datalogger, several temperatures were able to be recorded with a shorter time interval between recordings.

EXPERIMENTS

One of the first experiments that was done was to see where the best place for the stack is for maximum performance. A "mini-stack" was constructed using epoxied paper and spaced using pencil leads [4]. Thermocouples were placed on the stack, and it was found that the best place for maximum performance of the stack is within 2.5-cm of an end. Using this information, the next experiment could be performed.

The next experiment dealt with finding the optimal stack length. Since the stacks were easy to make, stirs and tape, 8 different lengths of stacks were made. They were then placed in the end of the refrigerator, Fig 1. There were thermocouples at both ends of the stack, so a temperature difference could be measured. The one end of all the stacks were placed in the same position. The experiments were also run under the same power. The data (table 1) shows that the performance increases, but not linearly as the stack length increases. The stack length used for most of the experiments is 9-cm in length. These lengths are not listed in the table, but have been found to produce desirable results.

Table 1

Stack Length (cm)	Voltage (mV)
1.68	0.74
2.13	0.91
2.54	1.18
3.10	1.41
3.33	1.51
6.99	2.40

The voltage is measuring the temperature difference, by using thermocouples, across the stack. With a copper-constantan thermocouple, every 0.04-millivolts is equal to 1 °C difference in temperature. Since this experiment was performed using Model 1, there was no heat exchanger, so there was heat build up at the one end. The voltages are not representative of a temperature drop, but rather a temperature difference between the two sides.

After this information was found, the maximum performance of the refrigerator could be found. A 9-cm stack was placed inside the refrigerator, Fig 2. Copper-constantan thermocouples were placed throughout the tube to monitor the temperature. The thermocouples were then run into the Datalogger. The Datalogger could record the temperatures over very short intervals, and this allowed us to find the heat pumping of the thermoacousic refrigerator. The heat pumping power of the refrigerator was calculated by placing a known mass on the cold side of the stack. The temperature of the mass was then recorded when the driver was turned on. The temperature was then monitored, and the heat pumping power could then be calculated by:

$$P_H=(mC\Delta T)/(\Delta t). \qquad (2)$$

In this case m was 33.3-g, C was 0.9-J/(g)(°C), and ΔT was 0.63°C, for a Δt of 60 seconds. This then gives a value of 0.32-watts for the heat pumping power of the system. After this value was calculated, the Coefficient of Performance was able to be calculated. First the fraction of acoustic power that returns every oscillatory cycle of the system had to be calculated. This is the fraction

$$A=[(1+R)/(1-R)]. \qquad (3)$$

In this case R, the average peak-to-dip ratio of pressure as the frequency is increased with constant excitation, was measured to be 4.1, which gives A a value of 39%. This means that the driver has to deliver 61% of the acoustic power to make up for the losses in the tube. The total acoustic power inside the tube was calculated to be 2-watts using the equation

$$P_T=(0.5)(\pi r^2)(p/2)^2/\rho c \qquad (4)$$

when r is 0.05-m, p is 893.4-N/m , c is 343 m/s, and ρ is 1.161 kg/m . That means that the acoustic power delivered by the driver is 1.2-watts. Using this number, the Coefficient of Performance (COP) could then be calculated by using:

$$COP=P_H/P_D \qquad (5)$$

With the heat pumping power at 0.3-watts, and the delivered acoustic power at 1.2-watts, the Coefficient of Performance is equal to 0.25.

OTHER FACTORS

One of the problems encountered during the experiments was the transfer of heat through the walls of the tube. The maximum drop in temperature depends on the transfer of heat from the cold end of the stack to the hot end of the stack. If the heat transfer through the walls of the tube equals the heat transfer through the stack, then the temperature of the cold end remains constant. If we decrease the transfer of heat through the walls, the temperature of the cold end should decrease. Insulation was then used in conjunction with some manufactured parts to decrease the heat transfer through the walls. This did not help the performance based on the results, which will be discussed later.

Another problem encountered is the sound level outside of the tube. The sound level pressure inside the tube is in excess of 150 dB SPL. The walls of the tubes are not very rigid, or very massive, so the sound level outside of the tube reaches undesirable levels. Putting more pressure on the ends by tightening up the nuts on the threaded rods to strengthen the walls, and by adding more mass helped slightly, but the sound levels are still more than desirable. Model 1 was usually placed in an anechoic chamber, so the sound levels were not perceived by the people around. A more reasonable approach is needed, so that the refrigerator can be used as a demonstration model in classrooms.

Another thing that was observed was the lowest temperature the refrigerator could achieve. This experiment was done under several different conditions, to see how the factors affect the final temperature. First Model 2 was run as it is shown in Figure 2. Air was the medium inside the tube. For the next part, insulation was placed around the tube, so the heat transfer through the walls would be decreased. Air again was used as a medium inside the tube. Finally helium was placed in the tube, and allowed to run, to find the lowest temperature that could be obtained.

FURTHER EXPERIMENTS

There were many comparisons made during the experiments. The first experiments that were done involved no insulation at all on the tube. This allowed a fair amount of heat transfer through the wall. Because of this, the temperature inside the tube did not get very cold. Four inch PVC couplings were manufactured so as to slide over the tube. Expanding foam was then placed between the tube, and the couplings. After that was done, water heater insulation was wrapped around the tube. This would then decrease the heat transfer through the walls, and should allow a greater drop in temperature inside of the tube.

Another comparison that was made was the comparison of performance for an air medium versus a helium medium. Helium was pumped slowly through the resonant tube, so the tube contained all helium, and no air. The refrigerator was then run, and the temperature drop was monitored.

A comparison was made early on dealing with the ability to cool a mass in the tube. For most of the experiments, only the air temperature inside the tube was monitored. For other experiments, a known mass was placed in the tube, and again the temperature inside the tube was measured, but also the temperature of the mass was measured. The mass placed on the cold end of the stack which was used in most of the cases was a section of air conditioning coil similar to the piece used for the heat exchanger on the hot end. The specific heat of the mass was known, so the heat pumping of the stack was able to be calculated.

RESULTS

In Model 2, with air as the medium, and no insulation on the tube, the temperature inside the tube dropped 5.4°C in 3 minutes, 5.7°C in 5 minutes, and finally dropped 8.5°C after sometime. The tube was then insulated, and the experiment was run again. This time the temperature dropped 5.8°C in 3 minutes, 6.4°C in 5 minutes, and achieved an overall drop of 7.5 °C. Finally, helium was then placed in the tube. After 3 minutes, the temperature drop was 1.1 °C, 1.3°C after 5 minutes, and 1.5°C for a maximum temperature drop.

Several conclusions can be made from this data. Comparing the insulated to the uninsulated, the results are very close. This would suggest that the heat transfer through the walls is not significant enough to create any losses in performance for this model.

Another experiment was done that backed up this conclusion. Liquid nitrogen was placed in the tube, to cool the inside. The temperature inside the tube was then monitored and the rate of temperature change was found. Using that data, and assuming that most of heat leakage was inward through the walls of the tube from outside, an ideal temperature inside the tube was calculated and was found to be much lower than the temperatures achieved during the experiments. The conclusion that can be made from that is that there must be some other limiting factor in the refrigerator.

These results may not be all that impressive, but you must also remember that the refrigerator was built using materials costing less than $30, and a speaker that costs $45. With that price range in mind, and the fact that some cooling is perceivable, this could very well fit into a high school curriculum, and there is also much room for improvements on the model.

CONCLUSIONS

Using inexpensive materials, a thermoacoustic refrigerator model can be built. This model can be used to show that cooling by using sound waves is possible. The model is also easy to build, even a high school class could build one. Even though the temperature drop of this model is not even close to temperatures obtained by other more expensive models, this cheaper model is practical for the average school to buy. Several of the values calculated can be compared to the models of Garrett and Swift. This gives hope to the thought that acoustic refrigeration may be an inexpensive alternative to other refrigeration technologies. There are still many problems with the inexpensive models, but for all practical purposes, they can show an area of physics that was almost unknown only a decade or so ago.

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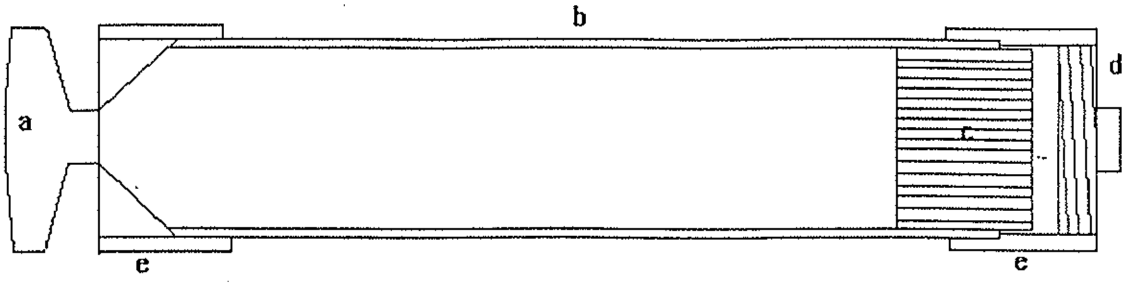

Figure 1 Schematic of acoustic refrigerator, Model 1
(a) 75-W horn driver, (b) 4-inch PVC tubing, (c) Stack, (d) End cap, (e) PVC connectors

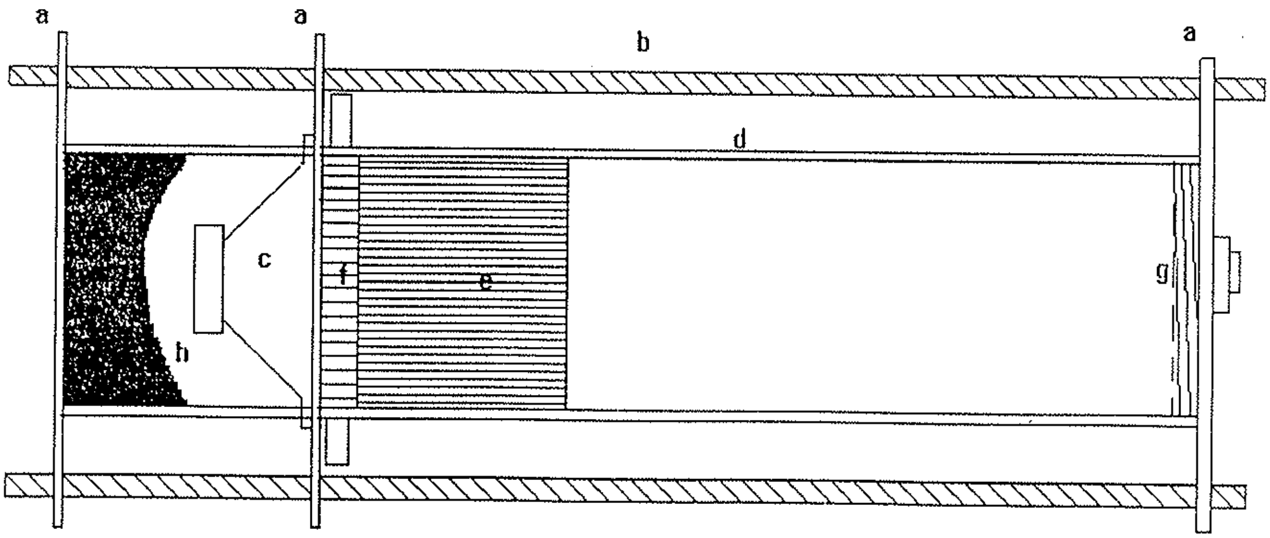

Figure 2 Schematic of acoustic refrigerator, high school model
(a) 6-inch square aluminum plates, (b) Threaded rods, (c) 4-inch, 40-W Zalytron speaker, (d) 4-inch PVC tubing, (e) Lexan stack, (f) heat exchanger, (g) end cap, (h) cement