# Design and Construction of a Simple Standing Wave Thermoacoustic Refrigerator

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**Abstract:** Refrigeration systems that are both efficient and have the least environmental issues are favored over those that pose harmful effect to the environment and human beings. At present the most widely used refrigeration system is the vapor compression system which is considered to be highly efficicient, however, the refrigerant used for this system contribute to the harmful environmental effects. Indicators of such inlcude the global warming potential and the ozone depletion potential. One of the greenest refrigeration system is the thermoacoustic refrigeration technology that make use of sound waves to produce a cooling effect. In this study, a simple thermoacoustic refrigerator intended for demonstrating the basic concepts of thermoacoustic refrigeration was constructed. The refrigerator made use of a simple resonator tube, a stack using celcor ceramic as the material and an audio source that produced the required sounds. The length of the stack was varied while the performance of the system was determined at constant frequency and power. The temperature of the cold side and the hot side of the system were measured during the testing. Results showed that the optimum performance of the thermoacoustic refrigeration system was attained when the length of the stack was 3.5 cm. In this configuration the maximum efficiency was attained at 42.96% and the maximum temperature drop at the cold side was 6°C. The maximum temperature difference between the hot side and the cold side was also obtained at this length and is equal to 17.4°C. Further studies to improve the performance of this thermoacoustic refrigerator is recommended.

**Key Words:** sound waves, thermoacoustic refrigeration, stack

## 1. INTRODUCTION

The types of refrigeration system that are being favoured nowadays are those that are both efficient and have the least environmental issues. These systems pose less harmful effects to the environment and human beings. At present the most widely used method of refrigeration system is the vapour compression system, however, there are issues with the refrigerants being used. These refrigerants contribute to harmful environmental effects and the indicators of such include the global warming potential (GWP) and ozone depletion potential (ODP).

Alternatively, one of the greenest way of refrigeration is through the use of thermoacoustic technology. The first noted discoveries of the thermoacoustic effect dates back to the 1800's with glass blowers in Europe where sound was produced from a temperature gradient applied on a tube. At present, thermoacoustic refrigerators and engines are not a viable commercial unit because of its disadvantages most notably in efficiency. On the other hand, there is significant need for this type of refrigeration for military and space applications.

Despite its low efficiency, there is the advantage of no moving parts and no refrigerants which also means less maintenance, longer operating life, and environmental friendliness. Thermoacoustics is the use of sound waves to create a refrigeration effect instead of the conventional system. Since air-conditioning and refrigeration has become a modern society necessity, turning it green will surely save our environment in the future.

## 1.1 Standing Wave Thermoacoustic Refrigeration System

Standing wave thermoacoustic refrigerators works through a standing wave thermoacoustic cycle. For a thermoacoustic cycle to work, every part of the thermoacoustic refrigerator has to be considered such as the gas, the stack, the tube, and the stack position. Figure 1 shows a simple design of a standing wave thermoacoustic refrigerator. The driver is the sound source of the system producing sound waves of the right frequency to cause temperature change. The resonance tube encloses the sound waves and the stack and at the heart of it all is the stack because this is where primary heat exchange happens.

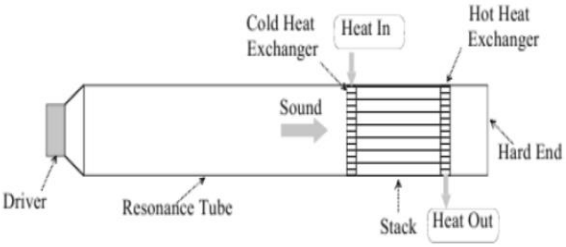

Figure 1: A simple design of a standing wave thermoacoustic refrigerator (Rietdijk, 2010)

## 1.2 Thermoacoustic Cycle

The thermoacoustic cycle of a standing wave heat pump involves four different processes. The ideal cycle for a thermoacoustic cycle using standing waves involves two reversible adiabatic and two reversible isobaric heat transfer processes. This can be simplified as follows:

**Process 1-2:** Gas parcel is adiabatically pressurized through compression. This heats up the gas parcel because of the pressure but no heat transfer occurs. During compression, gas parcels are displaced toward the hot side of the stack.

**Process 2-3:** The heated gas is hotter than the stack thus transferring heat from the gas parcels to the stack walls. This is an isobaric process so no pressure change occurs. Pressure and displacement are in phase so the gas parcels aren't moving while transferring heat to the stack.

**Process 3-4:** Gas parcel is adiabatically depressurized through expansion. This lowers the temperature of the gas parcel given lower pressure although no heat transfer occurs. Displacement of gas is towards the cold side of the stack.

**Process 4-1:** Isobaric process - Gas parcels absorb heat from surrounding environment. The cycle starts again.

Figure 2 shows a diagram of the thermoacoustic cycle.

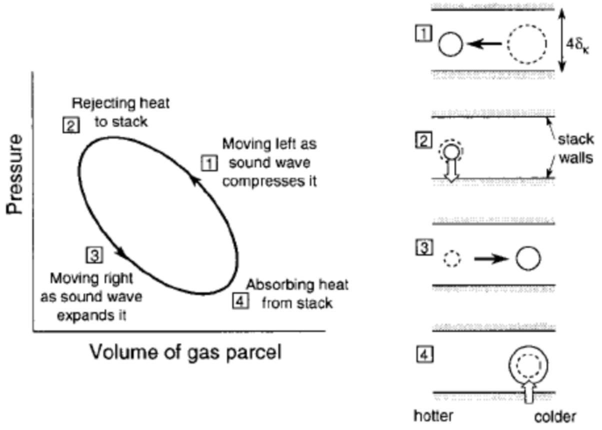

Figure 2: Diagram of the thermoacoustic cycle following the gas parcel on the right. Pressure-volume diagram of a gas through the thermoacoustic cycle on the left (Russel and Weibull (2002)

This study focuses on the design and fabrication of a working thermoacoustic heat pump as a refrigerator for demonstration purposes. Its objective is to demonstrate the theory of standing wave thermoacoustic refrigeration and to compare the performance of the system using three different stack lengths using celcor ceramic material. As a means of evaluating the results, only the Carnot efficiency and the temperature data will be used to measure the performance of the system.

## 2. METHODOLOGY

The stack used in this design is a Corning Celcor Ceramic stack considering that this is already widely used as a stack for thermoacoustic refrigeration system. The Corning Celcor Ceramic material which has 400 cells per square inch was obtained from Penn State. It was tested on lengths of 4 cm, 3.5 cm, and 3.0 cm. The 4cm was a direct reference to works by Russell and Weibull (2002) and Tasnim et al (2011) while the 3cm and the 3.5cm were made to see how the shorter resonator tube lengths may have affected the optimal stack length. Figure 3 shows the Corning Celcor ceramic used.

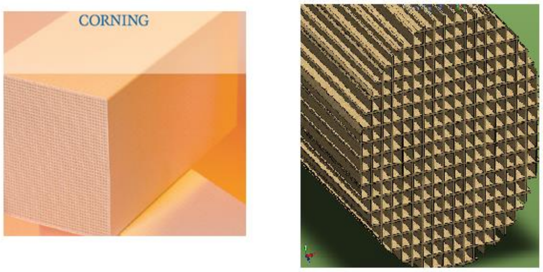

Figure 3: actual celcor ceramic (Corning) and solid works representation of stack

The resonator tube used was a Pyrex test tube from Penn State having an inner diameter of 2.24cm and overall inner length of 199mm. The length and the diameter are based on Russell and Weibull (2002) and Tasnim et al (2011) although the resonator tube length used is shorter by 30mm and 40mm for both works respectively. A 150 watts max pioneer TS-F1034R speaker was used. This was connected to an amplifier and a function generator which is capable of producing frequencies well above 200Hz. An acrylic plate was used to connect the resonator tube to the speaker.

K-type chromega – alomega type of thermocouples were used for measuring the temperature on the cold side and the hot side of the stack. One thermocouple was place at the top surface of the stack which was actually the hot side while another thermocouple was placed at the bottom surface facing the driver which was actually the cold side of the stack. Both thermocouples were connected to a digital thermometer which registerered the temperature for both the cold side and the hot side of the stack. Figure 4 shows a model of the set-up while the real set-up used during testing is shown in Figure 5.

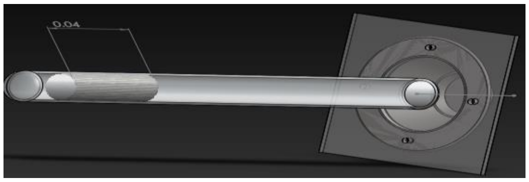

Figure 4: standing wave thermoacoustic refrigerator model

Figure 5: Set-up of actual thermoacoustic refrigerator

Testing was made on three different stack lengths at the same frequency and the same power. The temperatures were measured at the start for the reference value and were measured again every thirty seconds for three minutes for the hot side side and the cold side. The optimal frequency was found to be the same for all configurations and also well below the calculated frequency. As previously stated, the speakers and also the speaker-resonator tube coupling can affect the actual optimal frequency of the system which is different from the calculated resonant frequency of the resonator tube alone. The temperature of both the hot end of the stack as well as the cold end was measured using the setup configuration explained above

The efficiency of the system was measured using the equation, $\eta = 1 - \frac{Tc}{Th}$ where η is the efficiency, $T_c$ is the temperature at the cold side and $T_h$ is the temperature at the hot side. This is the conventional equation used in measuring the efficiency of a simple refrigerator which operates on a reverse Carnot Cycle. This will give us the performance of the stack in terms of how efficient the stack is in converting the given acoustic power into heat pumped from one side to the other. The work done here is considered to be the amount of heat moved from the cold side to the hot side thus decreasing the cold side temperature and increasing the hot side temperature. The output desired is then the amount of temperature drop or the cooling on the cold side given the heat pumped by the acoustic power.

## 3. RESULTS AND DISCUSSION

Tables 1, 2 and 3 show the measured temperatures of the cold side ($T_c$) and hot side ($T_h$) of the stack for the various lengths of the stack.

Table 1: Temperature data for the 4 – cm stack

| 4-cm stack | | 0s | 30s | 60s | 90s | 120s | 150s | 180s |
|---|---|---|---|---|---|---|---|---|
| 1 | Th | 28.5 | 34.4 | 36.7 | 37.7 | 38.4 | 38.9 | 39.3 |
| | Tc | 28.5 | 25.3 | 24.6 | 24.5 | 24.4 | 24.4 | 24.4 |
| 2 | Th | 28.9 | 34.4 | 36.6 | 37.8 | 38.3 | 38.9 | 39.2 |
| | Tc | 28.7 | 25.1 | 24.8 | 24.7 | 24.6 | 24.5 | 24.6 |
| 3 | Th | 29.1 | 34.9 | 37.3 | 38.5 | 39.1 | 39.4 | 39.5 |
| | Tc | 28.9 | 25.7 | 25.3 | 25 | 24.9 | 24.8 | 24.8 |
| 4 | Th | 29.3 | 34.9 | 37.1 | 38.2 | 38.9 | 39.3 | 39.7 |
| | Tc | 29.1 | 25.5 | 25.2 | 25.1 | 25.1 | 25 | 25.1 |
| 5 | Th | 29.4 | 35.4 | 37.4 | 38.2 | 38.7 | 39 | 39.2 |
| | Tc | 29.2 | 25.9 | 25.5 | 25.2 | 25.1 | 25.1 | 25 |

Table 2: Temperature data for the 3.5 – cm stack

| 3.5-cm stack | | 0s | 30s | 60s | 90s | 120s | 150s | 180s |
|---|---|---|---|---|---|---|---|---|
| 1 | Th | 29.3 | 36.3 | 37.7 | 38.3 | 40 | 40.3 | 40.5 |
| | Tc | 29.1 | 24.2 | 24.5 | 23.5 | 23.1 | 23.1 | 23.1 |
| 2 | Th | 29.4 | 36.3 | 37.8 | 38.4 | 39.9 | 40.3 | 40.6 |
| | Tc | 29.3 | 24.2 | 24.7 | 23.6 | 23.3 | 23.4 | 23.3 |
| 3 | Th | 29.4 | 36.1 | 38.1 | 38.5 | 39.6 | 40.1 | 40.4 |
| | Tc | 29.3 | 24.7 | 23.8 | 25 | 23.4 | 23.6 | 23.6 |
| 4 | Th | 29.6 | 36.4 | 38.4 | 38.2 | 39.8 | 40 | 40.4 |
| | Tc | 29.4 | 24.6 | 24.2 | 25.1 | 23.7 | 23.5 | 23.6 |
| 5 | Th | 29.7 | 36.3 | 38.4 | 38.2 | 39.7 | 40 | 40.2 |
| | Tc | 29.5 | 24.7 | 24.1 | 25.2 | 23.7 | 23.7 | 23.6 |

Table 3: Temperature data for the 3 – cm stack

| 3-cm stack | | 0s | 30s | 60s | 90s | 120s | 150s | 180s |
|---|---|---|---|---|---|---|---|---|
| 1 | Th | 29.9 | 36.3 | 38 | 38.6 | 38.8 | 39.1 | 39.1 |
| | Tc | 29.8 | 25.8 | 25 | 24.6 | 24.3 | 24.3 | 24.1 |
| 2 | Th | 29.5 | 35.8 | 37.5 | 38.2 | 38.6 | 38.8 | 38.9 |
| | Tc | 29.3 | 25.4 | 24.7 | 24.3 | 24.3 | 24.2 | 24.2 |
| 3 | Th | 29.6 | 35.7 | 37.5 | 38.2 | 38.5 | 38.7 | 38.8 |
| | Tc | 29.6 | 25.6 | 25.1 | 24.9 | 24.7 | 24.5 | 24.5 |
| 4 | Th | 29.5 | 35.7 | 37.4 | 38.1 | 38.5 | 38.7 | 39 |
| | Tc | 29.4 | 25.6 | 25 | 24.9 | 24.7 | 24.7 | 24.8 |
| 5 | Th | 29.3 | 35.7 | 37.3 | 38 | 38.4 | 38.6 | 38.8 |
| | Tc | 29.1 | 25.3 | 24.9 | 24.7 | 24.7 | 24.8 | 24.8 |

Figures 6, 7, 8, 9, and 10, on the other hand, shows the graphical representation of the temperature difference between the hot and cold side temperatures for the five different trials made.

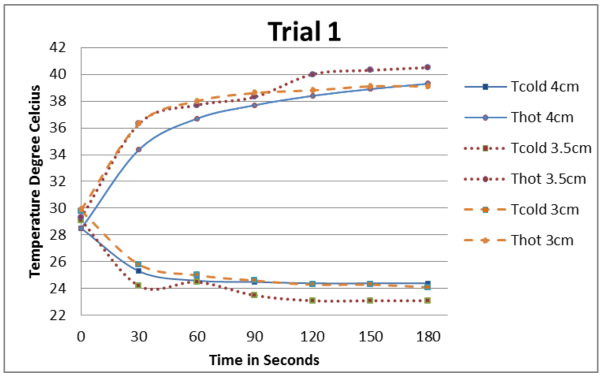

Figure 6: Temperature difference between the hot and cold side of the stack for trial 1

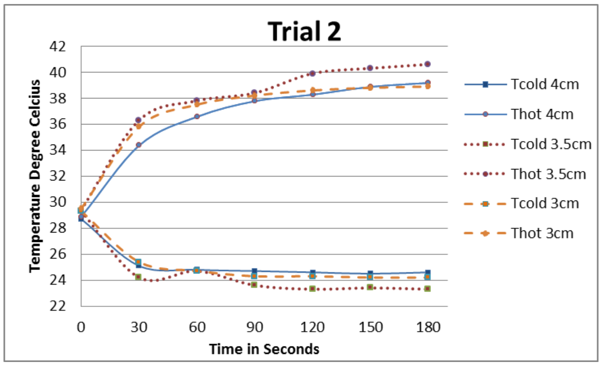

Figure 7: Temperature difference between the hot and cold side of the stack for trial 2

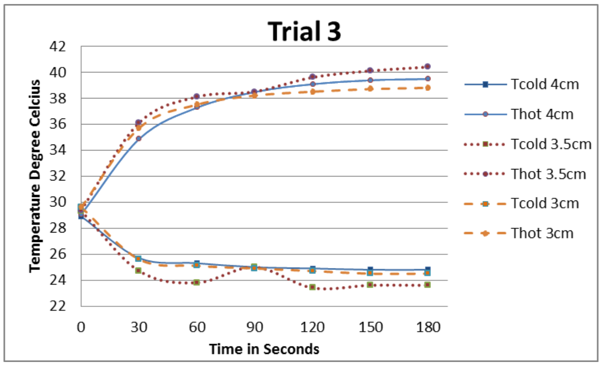

Figure 8: Temperature difference between the hot and cold side of the stack for trial 3.

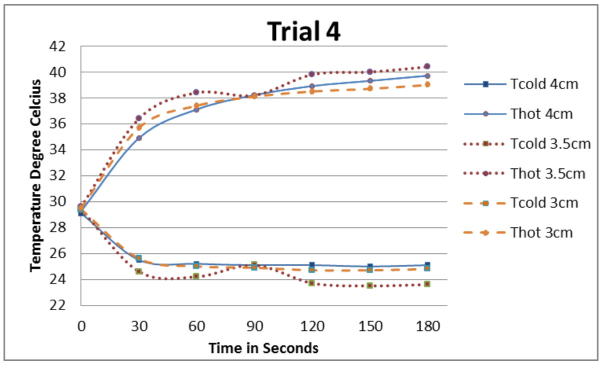

Figure 9: Temperature difference between the hot and cold side of the stack for trial 4

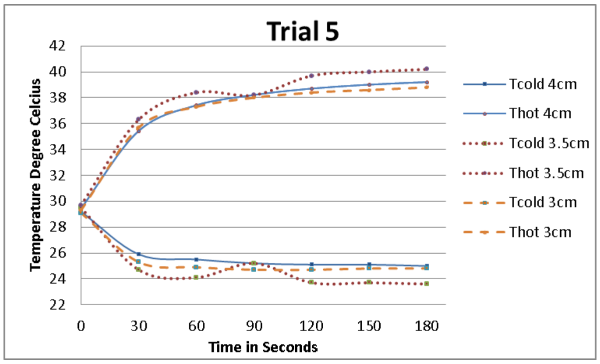

Figure 10: Temperature difference between the hot and cold side of the stack for trial 5

By examining the graphs, it can be seen that the 3.5cm stack not only has the highest temperature change, but it is also able to achieve the lowest temperature drop at the cold side compared to the 3cm stack and the 4cm stack. At a stack length of 3.5 cm, the highest temperature difference attained was 17.4°C while the maximum temperature drop at the cold side was 6°C. This means that for the amount of acoustic power presented, it is the most efficient configuration for the setup of this study in terms of turning acoustic power into cooling power. The maximum temperature difference attained was 14.9°C and 15°C for the 4 – cm and 3 – cm long stack, respectively. For the maximum temperature drop at the cold side, the value atained was 4.2 °C for the 4 – cm long stack and 5.7°C for the 3 – cm long stack.

The problem with the 3-cm stack length is that its length being the shortest, also makes it the most susceptible to unwanted heat transfer from hot side to cold side of the stack. The 4-cm long stack has its advantages in that its long length will mean it would be able to handle larger heat capacities and there will be less apparent heat transfer from hot to cold side, but the problem is that this would also cause the most viscous losses compared to the other stack configurations. The 3.5-cm stack is then the optimal stack length because it has the best balance of reduced viscous loss compared to the 4-cm stack and compared to the 3-cm - stack, it allows less heat transfer from hot to cold side while also having more heat capacity than the 3-cm stack.

The measured efficiency for the 5 trials for the three different configurations is shown in Table 4. The temperature used for all configurations is the one measured after 3 minutes. This is because at this point, the system is most stable with regard to the amount of temperature change for both the hot side and the cold side given the continuous flow of time compared to the other time intervals below 3 minutes. It can be seen that the highest efficiency of 42.96% was obtained when the stack length is 3.5 cm.

Table 4: Efficiency of different configurations measured at different trials

| Carnot Efficiency | Stack Length | | |
|---|---|---|---|
| Trial | 4cm | 3.5cm | 3cm |
| 1 | 37.91 | 42.96 | 38.36 |
| 2 | 37.24 | 42.61 | 37.79 |
| 3 | 37.22 | 41.58 | 36.86 |
| 4 | 36.78 | 41.58 | 36.41 |
| 5 | 36.22 | 41.29 | 36.08 |

## 4. CONCLUSIONS

The fabricated working thermoacoustic heat pump provided a temperature difference between the hot – side and the cold – side of the stack with a maximum value of 17.4°C at a stack length of 3.5 cm. At this length of the stack, the maximum temperature drop at the cold side is 6°C. This yields a maximum efficiency of 42.96%.

Some notes and recommendations are made for anyone attempting to undertake a standing-wave thermoacoustic refrigeration system. For the acoustic system, it should be noted that merely calculating the resonant frequency of the tube alone is not enough given how the coupling of the tube and the speaker actually affects the resonant frequency so it helps to vary the frequency up and down from the calculated frequency. The use of Celcor Ceramic for as stack which is available at Penn State is recommended because fabrication of the stack can be prone to errors. To further address acoustic power losses, a reducer cone can be made from the speakers to the resonator tube. As for the cooling power losses, this can be greatly reduced by making use of heat exchangers. An acrylic tube is also recommended since it offers more room for flexibility such as easy modification of the tube itself to consider changes in the acoustical behaviour.

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