An experimental study on the effect of various stack materials on thermoacoustic refrigeration effect

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Abstract. Thermoacoustic Refrigeration is a phenomenon in which cooling takes place by using high-intensity sound waves, which is gathering attention of many researchers in recent days. This alternative environment friendly technology could play an important role in near future. The paper is mainly an experimental case study on a thermoacoustic refrigeration system build in a laboratory environment with the commonly available materials. The setup was tested for various frequencies of sound to observe its effect on the drop of temperature. The refrigeration effect was also studied for various stack materials. It was observed that sinusoidal waves are better responsive to the production of the refrigeration effect. Moreover, the effect is more pronounced for paper-foil made stack.

1. Introduction
Thermoacoustic refrigeration process is a phenomenon in which high-intensity sound waves are used in an air-tight pressurized gas tube to produce refrigeration effect. In this refrigeration process, all sort of refrigerants that are conventionally used, are removed and sound waves take their place in presence of a loudspeaker in an acoustically insulated tube, called a resonator. This system eliminated the need of lubricants as there is no compressor is used and results in nearly 40% less energy consumption due to little or no moving parts, making them a highly efficient eco-friendly alternative with almost zero maintenance cost. If a stainless steel tube is kept on one side at room temperature and the other side in contact with liquid helium at 4 K, spontaneous oscillations are observed which is named ‘Taconis oscillations’ (2). Nikolaus Rott (1) established the mathematical foundation of thermoacoustics. Later, John Wheatley (4) and Swift (3) also worked in this field which provides useful data in the literature. The advantage of having no moving parts, the thermoacoustic devices are quite attractive for applications where reliability is of key importance. This System primarily consists of a loudspeaker attached to an acoustic resonator filled with a gas (Fig. 1). A stack which having a number of parallel plate like structure, is installed inside the resonator tube. The loudspeaker acts as the acoustic driver of the experimental system and also sustains acoustic standing waves in the gas inside the resonating tube (Fig. 2). The gas inside the stack medium is displaced by the acoustic standing waves. The heating and cooling of the gas present inside the resonating tube occur under the action of compression and expansion by the sound waves. The gas which cools due to the expansion are absorbing heat from the cold side and heats up. After that due to compression by the sound wave, when it moves towards the hot side, it rejects the heat to the stack. Therefore, an acoustic heat pumping action from the cold side...
to the hot side is created by the thermal interaction between oscillating gas and stack surface. The average temperature does not change at a certain location for a single medium. In presence of a second medium in the form of a solid wall, heat is exchanged with the wall. Thus, a compressed parcel will reject heat to the wall while an expanded gas parcel takes heat from the wall. Most of the temperature difference is observed from expansion and compression of the gas due to the acoustic pressure created by the sound waves inside the resonating tube, and the rest is the consequence of heat transfer between the gas/air and the stack material.

![Figure 1. Schematic diagram of a thermoacoustic refrigeration system](image1)

The study of the thermoacoustic phenomenon in a theoretical way was done by Kramers, when he generalized the Kirchhoff theory of the attenuation of sound waves at a constant temperature as well as a temperature gradient in 1949. The acoustical part of thermoacoustics was connected by Swift (3) in a broad and vast thermodynamic framework. The Space thermoacoustic refrigerator was able to move about 50 Watts of heat. It was the first thermoacoustic chillier which was electrically driven and designed to operate outside a laboratory. The refrigeration system was run by using a compression driver which is connected with a quarter-wavelength resonator system. The device operated with 97.2% Helium and 2.7% Xenon gas mixture at a pressure of 10 bars. As a whole the standard arrangements for such systems are quite costly and alternative methods should be devised. Further experiments are also required to make the system cheap and eco-friendly while considering its effectiveness. Present work seeks an exemption from costly equipment to check the scope of commonly available materials on this aspect.

![Figure 2. Displacement of sound waves with pressure variation.](image2)

2. Materials and methods adopted for experimental setup
The experimental testing setup generally includes a compact thermoacoustic refrigeration system, a testing part and a data acquisition part. Fig. 3 explains the details of the experimental setup, which consists of the loudspeaker housing made with ply board, a stack and a resonating tube. The amplifier is connected with AC power supply and sound-producing attachments. Three main parts of the setup are the thermoacoustic refrigeration System consists of an air-tight and soundproof resonating tube, a stack part made of different materials, an acoustic driver or the loudspeaker and a heat exchanger. Test
section includes temperatures probes at the inlet part and the outlet part of the heat exchanger and at the middle portion of the resonator tube, at the surface of the acoustic driver. The Data Acquisition System consisting of thermocouples, transducer and mobile applications for producing desired frequency sound wave.

Figure 3. Schematic diagram of the experimental setup.

2.1 Acoustic Driver (Loudspeakers)

The primary component of a thermoacoustic cooling device is an acoustic driver which is attached to one end of the resonator. This creates an acoustic standing wave in the gas at the fundamental resonant frequency of the resonator. It is powered by an electrical power source. A function generator drives the loudspeaker and to excite the working fluid inside the resonator, a power amplifier is provided. This type of loudspeaker has relatively low efficiency due to limited range of pressure amplitudes inside the resonator. The loudspeaker used in the present study has a maximum power of 20 watts at 225 Hz operating frequency.

2.2 Stack

Stack is the most essential component of a thermoacoustic system where the major phenomenon occurs. Therefore the performance of the thermoacoustic device is governed by the nature of the stack. Low thermal conductivity is an essential property for a stack material that helps to reach high temperature gradient across the stack. A larger heat capacity than the working fluid is desirable for the stack material. Moreover, the material should minimize the effects related to viscous dissipation of acoustic power. To provide a medium where the walls are close enough, stack is used. It is made in such a way that each time a packet of gas moves, the temperature differential is transferred to the wall of the stack. The use of honeycombed plastic spacers has been reported in much literature where the stack absorbs heat locally instead of conducting through the stack. Similar structure has been prepared in the present study using paper, aluminium foil and thermal transfer barcode labels ribbon. The spacing of these designs is crucial. Too narrow holes are difficult to fabricate, and in that case the viscous properties of the air make it difficult to transmit sound. Moreover, if the walls are too far apart, the resulting efficiency will be low due to less air will be transferring heat to the walls of the stack.

Figure 4. Paper made and Aluminium foil made Stack used for the experiment
2.3 Working Fluid
The selection of the working fluid depends on various parameters like power, efficiency, cost and operational convenience depending on the application. It has been detected that thermoacoustic power increases with the increasing of the local sonic velocity of the experimental working fluid. As discussed, costly inert gases like Helium or neon are favoured as a working fluid. However, in the present case study normal ambient air has been used for the experimentation to check its range of applicability.

2.4 Acoustic Resonator
The acoustic resonator is made of a straight acrylic glass tube of 5 cm internal and 5.8 mm wall thickness. A ply board is attached with it to install the speaker frame at one end of the tube. The other end of the tube is sealed by woodblock and gluing.

2.5 Measuring Devices
An amplifier with 10 Hz to 110 kHz frequency response and 158 W power output, is used to amplify the loudspeaker. Digital thermometers (range 0 ºC – 150ºC) are used for measuring the temperature at different locations inside the resonator as well as that of heat exchanger fluids.

3. Experimentation

3.1 Common Assumptions
- Heat leakage from cold to hot side along the stack material and as well as the gas inside the resonating tube is negligible.
- The wavelength of the acoustic standing waves longer than the stack itself.
- Viscosity of the boundary layer is zero.
- Pressure inside the resonator is constant
- Steady state is maintained.

3.2 Design of Experiments
The experiments were carried out to observe the performance of the thermoacoustic system under various operating conditions like different sound frequency and different stack material. The frequency was changed slowly to observe the variations for each set of experiments. The nature of the wave was also varied like Sinusoidal nature, square nature, triangular nature and the results are collected. The experiments were carried out for 3 types of stack material namely Aluminum foil, Paper and photo film ribbon. The sound of different frequencies with different nature is produced by an android application named ‘Frequency Generator’. Initial data was taken only when the system reached steady state at the set condition and similarly data was collected at various other settings in the entire frequency range.
3.3 Experimental results
Initial experiments were conducted on the setup with stack position 7 inches from the end of the resonating tube. The results were noted by varying frequencies and wave nature for both the aluminium foil and paper-made stack. Reading was taken at a period of about 25 minutes. The results obtained are briefed in the following table 1:

| Wave Property | Temperature difference (°C) |
|---------------|-----------------------------|
| Frequency     | Paper Stack | Aluminium Foil stack |
| 110 Hz Sinusoidal | 2.8 | 0.5 |
| 110 Hz Square | 2.5 | 0.2 |
| 110 Hz Triangular | 2.7 | 0.9 |
| 125 Hz Sinusoidal | 3.0 | 1.1 |
| 125 Hz Square | 2.2 | 0.7 |
| 125 Hz Triangular | 2.8 | 1.2 |
| 135 Hz Sinusoidal | 1.6 | 0.9 |
| 135 Hz Square | 1.7 | 0.6 |
| 135 Hz Triangular | 2.9 | 1.1 |
| 160 Hz Sinusoidal | 0.9 | 0.6 |
| 160 Hz Square | 0.8 | 0.3 |
| 160 Hz Triangular | 1.1 | 0.9 |

4. Discussion of results
The observation demonstrates how the system performs on the different frequency of sound waves with different nature of waves, the dependence of working fluid, resonator shape and material at the length of stack on the system performance.

![Figure 6. Temperature drop with change in frequency for paper stack](image_url)
4.1 Effect of frequency and wave nature on Temperature Drop, for Paper-made Stack

Fig. 6 shows the variation of temperature with respect to variations of different frequencies (110Hz, 125Hz, 135Hz and 160Hz) is take place for the experimental paper Stack. The peak temperature drop is obtained by Sinusoidal wave with 125 Hz frequency for the paper stack. The Lowest temperature difference is obtained by the square wave with 160 Hz frequency. But on average consideration, the triangular wave gives more consistent results in all those 4 frequency variation. The square wave gives less temperature difference in all three natures.

4.2 Effect of frequency and wave nature on Temperature Drop, for Aluminum foils Stack

In Fig 7, the refrigeration effect is shown in terms of temperature differences with respect to varying frequencies of sound in the range discussed earlier for the experimental aluminum foil Stack. The peak temperature drop was obtained by triangular wave with 125 Hz frequency for the aluminum foil stack. The Lowest temperature difference is obtained by the square wave with 110 Hz frequency. But on average consideration, the triangular wave gives more suitable result in all those 4 frequency variation and having consistency in its data. The square wave gives less temperature difference in all three natures.

4.3 Effect of variations of stack material

Fig 8 demonstrates the peak temperature drop achieved for each frequency to exhibit the effect of stack material. It was found that paper stack is having more heat capacity then the aluminium foil made stack. The temperature difference is better between the two ends of the paper made stack because of the low thermal conductivity of paper. The Spacing between two stacks is also very crucial as it should not too tight or too loose. The bar chart shows that the peak temperature drop is 3.5 degree C for the paper stack which is obtained at 125 Hz frequency, where the aluminium foil made stake can give a maximum temperature drop is 1.2 degree C.

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**Figure 7:** Temperature drop with change in frequency for Aluminum foil stack

**Figure 8:** Peak temperature drop for both stacks with varying Frequency
5. Conclusion
The experimental case study presented in this paper had the primary objective of constructing a low cost design model of a thermoacoustic refrigerator and test its capabilities. The experimental results indicated the possibility of such systems for various household applications in a smaller scale. Additionally, the temperature drop happening in the both ends of the stack and their interrelationship with the sound frequencies, stack material and nature of wave was explored. The range of experimental parameters can be further stretched and constructional errors can be removed to achieve a more accurate and reliable conclusive results. Further experiments can be conducted with many more stack materials. Although the overall efficiency of such apparatus is still under research, thermoacoustic refrigeration has the potential of replacing conventional refrigeration as a sustainable alternative.

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