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Experimental Study of Thermoacoustic Refrigeration System for Different Stack Positions and Varying Frequencies

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Abstract - *Thermoacoustic Refrigerators use acoustic power for generating cold temperatures. The development of refrigerators based on thermoacoustic technology is a revolutionary answer to today's cooling needs that does not harm the environment. These devices can achieve very low temperatures while keeping a compact size, thanks to features such as limited moving components and the lack of CFC refrigerants.*

In this work experimental study has been performed on Thermoacoustic refrigeration system by using air as the working fluid. Focus of the present investigation is to see the effect of changing design and operating parameter on temperature gradient across the stack. Here the stack position has chosen as design parameter whereas for operating parameter frequency has been selected. The results obtained from the experiments have been discussed in result and discussion section of this report. The analysis shows that operating nearer to optimum designed frequency offers better results while stack position of 100mm offers comparatively better results when stack is at 50mm.

Key Words: Experimental analysis, Frequency variation, Stack material, Thermoacoustic refrigeration, Temperature measurement

1. INTRODUCTION

Thermo-acoustics is a field of acoustics and thermodynamics that explores how sound waves transport heat. Acoustics studies the effects of sound transmission, such as pressure changes and motion oscillations, whereas thermo-acoustics studies temperature oscillations. For a better understanding of the TAR, a basic grasp of sound and heat transport is required. It entails the investigation of interactions between temperature and pressure oscillations caused by sound waves in solid barriers.

Theory of Thermo Acoustics

From the basic physics of periodic sound waves [1], we get the equation for displacement:

$$s = s_{max} \sin (kx-\omega t) \quad (1)$$

And pressure

$$p = p_{max} \cos (kx-\omega t) \quad (2)$$

The wave number is k, the angular velocity is ω, the maximum displacement amplitude is s_{max}, and the maximum pressure amplitude is p_{max}.

From this, we can see that displacement and pressure are ninety degree out of phase. Swift showed that along with pressure there is also a temperature oscillation [2]. For an adiabatic sound wave propagating through an ideal gas, the temperature oscillations, T_1 are related to the pressure oscillations p_1, [3] as:

$$\frac{T_1}{T_m} = \frac{\gamma-1}{\gamma} * \frac{P_1}{P_m} \quad (3)$$

Where T_m and p_m respectively are the mean temperature and pressure of the medium, and γ is the specific heat capacity ratio.

The size of temperature oscillations in a medium like air at STP and pressure amplitude of typical conversation (60 dB) is roughly 10^{-4} °C and goes undetectable by human senses. The thermal interaction of sound waves with a different medium, such as a solid, can result in a considerable quantity of heat exchange between the fluid and the solid when working at high pressure amplitudes.

Thermo acoustic refrigeration is a type of refrigeration that applies thermo acoustic concepts to a real-world situation. Sound waves and a non-flammable mixture of inert gas (helium, argon, air) or a mixture of gases in a resonator create cooling in thermoacoustic refrigeration systems. Thermoacoustic devices are classified as either "standing-wave" or "traveling-wave" devices.

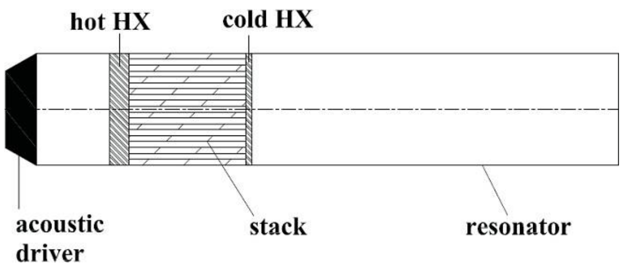

Figure 1 Schematic of Thermoacoustic refrigeration systems

To achieve better cooling effect and higher temperature gradient many experimental investigations have been done on the Thermoacoustic refrigeration system by changing the parameters of the setup. Many reviews are also given by many researchers on the behavior of the refrigeration in Thermoacoustic

Refrigeration system. Some of them are cited here with their contributions. Nemi Shah et al. [4] had done a review on Thermoacoustic Refrigeration system in which they considered the gas parcel which is oscillating in thin pore in the stack. From this they reviewed as gas parcel propagates from the speaker end to the right end in the pore where the pressure of the gas decreases due to expansion. As pressure decreases the temperature of gas parcel also decreases, so temperature difference occurs between two ends. Alwin Jose et al. [5] investigated the Thermoacoustic Refrigeration system by modifying the parameters, with the frequency as the independent variable, kept constant, and individual geometrical configurations such as porosity stack length and stack location as the dependent variables. When the stack is closest to the tube's closed end, the temperature differential is greatest. The goal of A.C Alock et al. [6]'s experimental examination of an adjustable thermoacoustically powered Thermoacoustic refrigerator was to see how the geometrical design of the stack affected the performance of the TAR. As a result, they calculated that the temperature differential created when the stack shape was modified was around 8 degrees. Evan Lobo et al. [7] they have designed and fabricated a Thermoacoustic refrigeration system and conducted experiment under different operating conditions and concluded that an appropriate temperature drop of 5 degrees Celsius was obtained and more temperature drop can also be obtained. They have also concluded that, Thermoacoustic refrigeration can be a potential alternative to existing system which is both cost effective and environmental friendly. Ashish S.Raut et al. [8] done design and optimization of stack for TAR and concluded that frequency effects the temperature in the system. The experiment was carried out with varied constant pressure and cooling load values, and it was discovered that when the pressure was raised, the stabilisation time rose. It was also observed that the temperature rose at first and then levelled out. Hemal Patel et al. [9] done a review on TAR and declared that performance of TAR depends on working gas, pressure, stack material, resonator tube, position and length of stack. Results they have obtained were without stack temperature is constant, after 18 minutes of observation they have obtained a temperature gradient of 7 degrees across the stack, the position of the stack was very important for maximum temperature gradient. K. Augustine et al. [10] done a critical review on TAR and its significance and they have concluded that TAR can reduce the emission of harmful gases like CFC because of the use of eco-friendly refrigerants like helium. The goal of the review is to put up a TAR with varied design characteristics. Florian Zink et al. [11] did an environmental motive to transition to TAR since their evaluations found that utilising TAR'S can reduce environmental pollution, particularly in areas with a lot of heat wastes, because heat wastes can be utilised and cooling can be done while reducing pollution. In circumstances when waste heat is abundant, the potential savings of environmentally damaging materials can be high enough to support a drive to employ TAR for lone time. Ravindra Edlabadkar et al. [12] conducted an experimental and theoretical study of low-cost standing wave thermoacoustic refrigeration, concluding that glass fibre with glass capillary tube spacers produces the largest temperature gradient, with a temperature difference of 11K at 0.15 K. m position from speaker inlet. They calculated a temperature differential of 6K at 0.15m stack distance from the speaker using numerical analysis. Parabadiya Amjadali Habibbhai et al. [13] conducted an experimental study of thermoacoustic refrigeration using a variety of gases and stack materials, concluding that the speaker's quality had an impact on the TAR's performance. They discovered that nitrogen gas using PVC as the stack material produces the biggest temperature gradient and cooling impact based on the trial results. Proper heat transmission and heat loss mitigation may improve TAR performance. In various instances, BammannT.C et al. [14] conducted a review of flow–through design in thermoacoustic refrigeration and concluded that TAR systems can be as efficient as vapour compression cycle refrigeration technology. Future investigation can be done and Thermoacoustic refrigeration systems can be used in industry. L. K. Tartibu. [15] Conducted experimental investigation for maximum cooling and minimum efficiency of Thermoacoustic refrigerators and concluded that the stack positions and geometry must be very necessary for the cooling effect. If the stack was located closer to the pressure antinodes then maximum coefficient of performance of the device is confirmed and maximum cooling is conformed when stack moves away from the pressure antinodes. Prajwal C. Bansod et al. [16] reviewed on Thermoacoustic refrigeration and also done experimental investigation and concluded that the stack position from the driver end should be critically optimize to get desired end but not exactly at driver end the results are severe when it is placed exactly at driver end. They have also concluded that Mylar can be the best stack material and mixture of helium and other inert gases improves the performance of the Thermoacoustic Refrigeration system. G. Praveen Kumar Yadav et al. [17] done experimental investigation on Thermoacoustic refrigeration system and concluded that they have yielded a temperature gradient of about 7 degrees, the effective performance can be noted when we use the stack materials and stack geometry in exact dimensions even the resonator length, stack geometry and many other parameters can be also exchanged for better output. Kaushik S. Panara et al. [18] done Thermoacoustic refrigeration system setup and concluded that finding the optimal frequency is essential for the maximization of efficiency. The optimal frequency was found using trial and error, the factor influenced the efficiency was the proper sealing of the apparatus. The heat loss can also affect the performance of the Thermoacoustic refrigeration system, so from this they concluded Thermoacoustic refrigeration system can be a replacement for normal refrigeration systems.

Nomenclature

A	Antinode
f	Frequency (Hz)
k	Wave number (m^{-1})
L	Length of the resonator tube (m)
L_s	Length of stack (m)
N	Node
p	Pressure (bar)
s	Displacement amplitude
T	Temperature (K)
t	Time (s)
v	Speed of sound (m/s)

X Geometric distance (m)

Greek symbols

γ Specific heat ratio

ω Angular frequency (rad s^{-1})

∆ Gradient

Subscripts

m Mean

1 Local amplitude

Acronyms

HX Heat exchanger

TAR Thermo acoustic refrigeration

2. PARTS DESCRIPTION AND EXPERIMENTAL SETUP

2.1 Major components

A Thermoacoustic Refrigeration system was fabricated in an easy way from the components which were available at the cheaper costs .The parts and description of the Thermoacoustic refrigeration system will be discussed here Parts of Thermoacoustic Refrigeration System

- Resonator
- Stack
- Loudspeaker
- Amplifier
- Temperature Indicator and Thermocouples

Wave generator

Figure 2 Acrylic tube as resonator

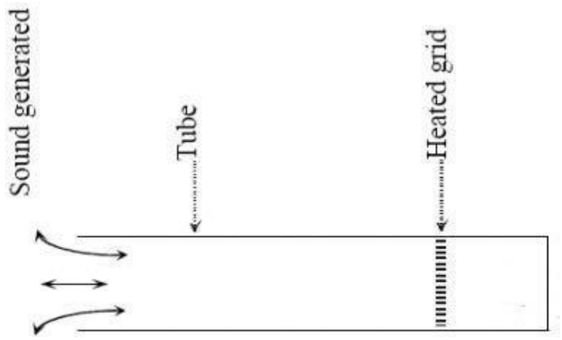

Figure 3 Standing sound wave propagation

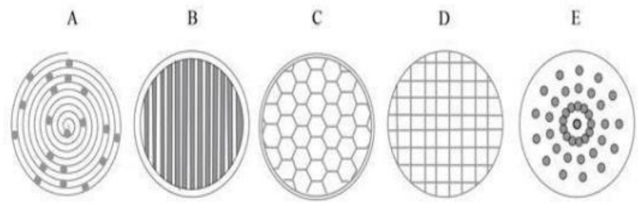

Figure 4 Stack geometries A. Spiral stack, B. Parallel plate, C. Honeycomb, D. Corning celcor, E. Pin array

Figure 5 Aluminium foil used as a stack

Figure 6 Loudspeaker

Figure 7 Amplifier

Figure 8 Thermocouples

Figure 9 Software function generator: (a) 150Hz frequency (b) 100Hz frequency (c) Different wave forms (d) Time setting option

2.2 Setup and working of Thermoacoustic Refrigerator system

Procedure

- Arrange a stand to place the equipment.
- It consists of an Amplifier which amplifies the sound waves that is connected to the Loud Speaker.
- The loudspeaker is connected to the one end of the Resonator through which the amplified sound waves passes into it.
- Inside the Resonator, Stack is placed through which the sound waves passes.
- The stack divides the Resonator into two regions.
- The amplified sound wave inside the resonator vibrates and expansion and compression takes place on either side of the stack.
- The compression region is the hot region and expansion region is the cold region.
- The temperatures on either side of the region are known by the temperature indicator.
- The Thermocouples are placed on either side of the stack and are connected to the indicator.
- The Temperature of both the regions is indicated in the temperature indicator.

The time taken to measure each reading is according to the experiment.

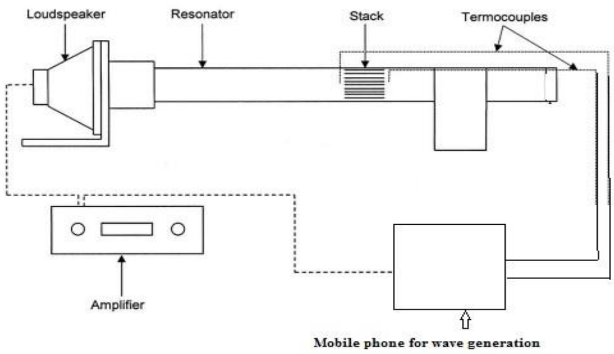

Figure 10 Schematic diagram of experimental setup

Figure 11 Experimental setup

Figure 11 shows the experimental setup of Thermoacoustic refrigeration system fabricated in the HT lab. The readings are shown in the temperature indicator just as shown in the figure.

Figure 12 represents the working of Thermoacoustic refrigeration cycle.

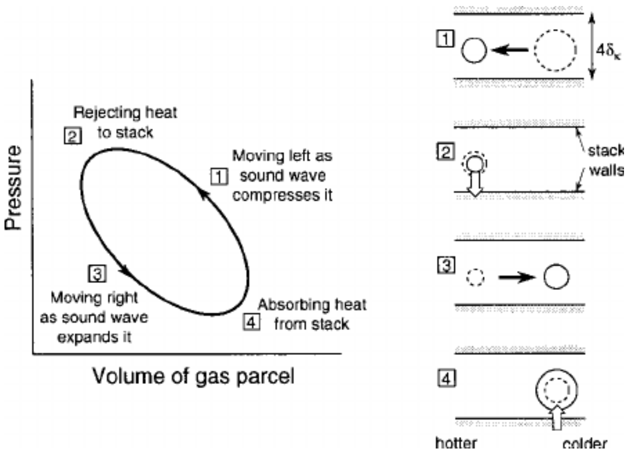

Figure 12 Thermoacoustic refrigeration working cycle

3. DESIGN SPECIFICATIONS

The table lists the different components used in the thermo acoustic refrigeration system fabrication with their specifications.

Table 1 Design specifications of components

S. No.	Component	Specification	Quantity	Material
1	Acrylic tube	D_i=110mm, L=600mm	1	Acrylic
2	Loud speaker & Amplifier	2500W	1	
3	Thermocouples	2m	2	
4	Temperature Indicator	6 Switches	1	
5	Stack	L=50mm	1	Aluminium foil

4. COST ANALYSIS

This particular table shows the cost of various components used to fabricate the complete experimental setup.

Table 2 Cost analysis of components

Component	Specification	Quantity	Cost (Rs.)
Acrylic tube	D_i=110mm, L=600mm	1	1600
Loud speaker & Amplifier	2500W	1	1450
Thermocouples	2m	2	200
Temperature Indicator	6 Switches	1	2000
Stack	L=50mm	1	100
Total			5350/-

5. RESULTS AND DISCUSSIONS

The experiments have been performed for two stack positions (50mm and 100mm) and two frequency variations (100Hz and 150Hz) based on the length of resonator tube [3] for about an hour. After every 10 minutes temperature readings were noted down for both the sides i.e. cold and hot side of the stack. The observed data has been analyzed with the help of various illustrative graphs and tables presented in this section.

Case 1: Stack length 50mm, Stack position 50mm, frequency 100Hz, Wave function Sine Wave

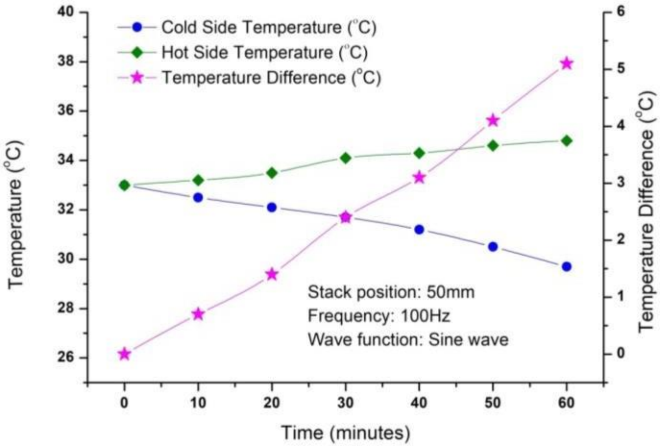

Figure 13 Time Vs temperature for case 1

Figure 13 depicts the temperature variation across the stack i.e. hot and cold end of the stack with time. The cold side temperature is decreasing little faster compared to increase in hot side of the stack which is in line with the concept of thermoacoustic refrigeration. The above figure also shows the temperature difference across the stack with time. Here for a frequency of 100Hz when stack is placed about 50mm from the driver end a temperature gradient of about 5.2 ^{0}C is achieved.

Case 2: Stack length 50mm, Stack position 50mm, frequency 150Hz, Wave function: Sine Wave

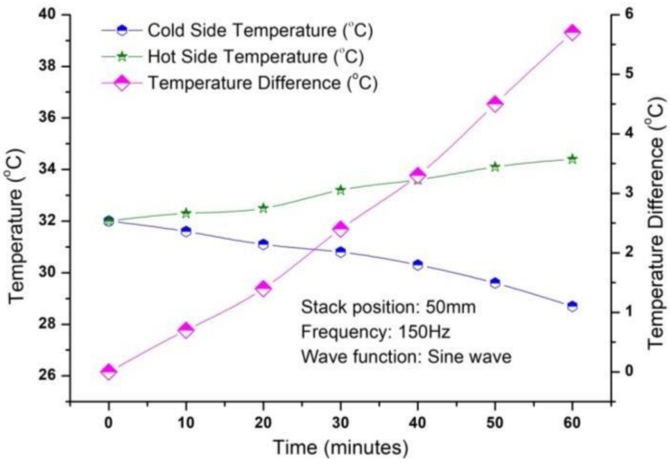

Figure 14 Time Vs temperature for case 2

From fig 14 the cold and hot side temperature variation with time can be seen for operating frequency of 150Hz. This figure shows the same trend as observed in the fig. 13 which is technically correct. The graph also shows the temperature difference in another Y axis. In this case the temperature difference achieved within a same time is little higher compared to previous case as this frequency is more nearer to the optimum frequency for tube length and velocity of sound in air [3]. Temperature gradient of about 5.7°C is achieved in this case which suggest that if operating frequency is nearer to optimum higher gradient can be achieved**.**

Case 3: Stack length 50mm, Stack position 100mm, frequency 100Hz, Wave function sine wave

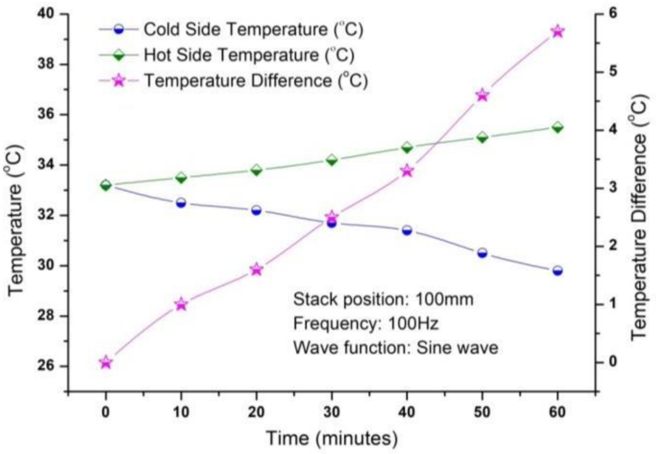

Figure 15 Time Vs temperature for case 3

Graph 15 illustrates the results when system was operated at stack position of 100mm and at a frequency of 100Hz. In this case the increase and decrease in temperature of hot and cold side is more linear compared to other cases. The temperature gradient achieved in this case is about 5.7 °C which is in line with the other cases.

Case 4: Stack length 50mm, Stack position 100mm, frequency 150Hz, Wave function sine wave

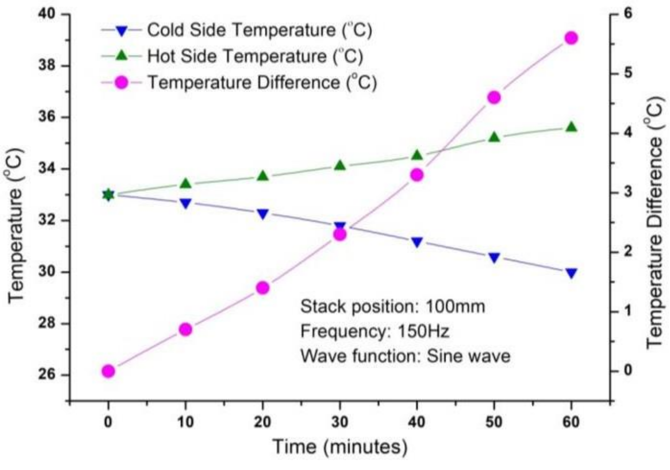

Figure 16 Time Vs temperature for case 4

5.1 Comparative analysis of all cases

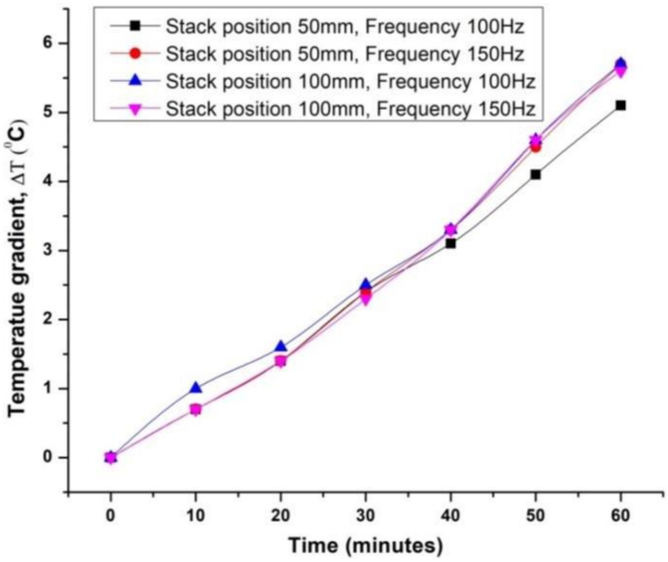

Figure 17 Time Vs temperature: Comparative study

Figure 17 shows a comparison of all cases with respect to maximum temperature gradient achieved in experimented time. Graph suggest that operating at frequency of 150Hz is giving better results compared to the 100Hz condition which also was expected as it is nearer to optimum frequency for size of resonator tube and velocity of sound. While analyzing the graph for better performance of system with respect to stack position it was observed that the 100mm stack position offers higher temperature gradient

6. CONCLUSIONS

Based on the results obtained and discussed in previous section the important conclusions have been made and listed as under:

- Experimental investigation has been done for different stack positions which were placed inside the Resonator with frequency variation.
- By comparative analysis it was concluded that operating nearer to optimum designed frequency provide better results so here 150Hz has been identified better between the two frequency taken for experiment.
- Stack position of 100mm is found better in terms of temperature gradient achieved during the experiment.
- From all the readings noted with different stack positions and varying frequencies it was concluded that there was a temperature difference of about 5.7°C degrees was obtained in 60 minutes of limited experiment.
- The experiment time taken was 60 minutes as after this time temperature variation is very slow.

The work provides an experimental idea to the researchers want to work in this field. Work also provides the information regarding some design and operating parameters effect on TAR system. We strongly believe that further researches in this field will open up opportunities to cool an auditorium or a stadium by the sound energy produced in it. Also it will be green idea in this era of increase global warming and energy scarcity.

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