Design and Fabrication of Simple Thermoacoustic Refrigerator

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Copyright Statement

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Abstract

Thermoacoustic refrigeration is a type of refrigeration, which is environment friendly and safe. This provides the broader scope for further research. Pros comprises of the presence of immovable parts and no release of toxic ozone depleting gases including cfcs and Freon. The combination of both disciplines, thermal and acoustics, is captivating the attention of many researchers. The core purpose of this experiment is to examine the working of stack by using the parameters related to thermoacoustic refrigerator and is considered to be as a heart of thermoacoustic system. Low cost and porous material was utilized in the system for the testing and study of performance. The variables, which are considered while examining the performance of the refrigerator, are length and position of stack. The guidance was taken regarding the geometrical configuration of stack.

Key Words: *Thermoacoustic Refrigerator, Stack Geometry, Random Material, Eco Friendly*

Table of Contents

List of Figures

CHAPTER 1: INTRODUCTION

According to Nicholas Rott, who provided theoretical groundwork for the field, the term thermoacoustics is “self-explanatory” [1]. Thermoacoustics deals with the sciences that talk about the gases about having association with the oscillation of pressure and heat. This discipline has further two sub-categories. Forward effect is the first category which characterizes oscillation of pressure produced due to heat. In early times, engines were created by this effect. Currently, in literature, these engines are named thermo-acoustic engines. The second category handles the reverse effect. The reverse effect addresses the pumping of heat due to acoustic waves. Primarily, the reverse effect provided the basis for the creation of refrigerators, known as thermoacoustic refrigerators. Moreover, thermoacoustic refrigerator is the topic of current study.

1.1 History

For the past few decades, the trails have been done for the creation of devices by using the thermoacoustic effect. The researches and studies have focused on this effect in recent times. In literature, many publications are accessible for reviewing the history of thermoacoustics [2, 3]. In 1777, Higgins [4] performed experiments on the generation of acoustic oscillation due to heat. Higgins mentioned that acoustic oscillations would take place when a flame of hydrogen would be positioned in a correct orientation within an organ pipe.

Rijke extended the work of Higgins [5]. Rijke used small heated screen within an organ pipe instead of a flame of hydrogen. These changes resulted in the production of acoustic oscillations. This particular tube was named as “Rijke Tube”. Tijani [3] and Feldman [6] discussed Rijke tube in detail.

The glass blowers had a signing effect for many decades. They took the observation of signing effect came from the bulbs they used. Moreover, Lord Rayleigh [7] also recorded the signing effect. Sondhauss [8] performed comparable experiments by using an apparatus of glass ball with connected neck. The joint of glass ball and attached neck was heated. The figure 1 provides the illustration of the experiment. This picture represents that sound waves are coming out from the portion of neck. These sound waves can only be heard when the system had acquired specific amount of heat.

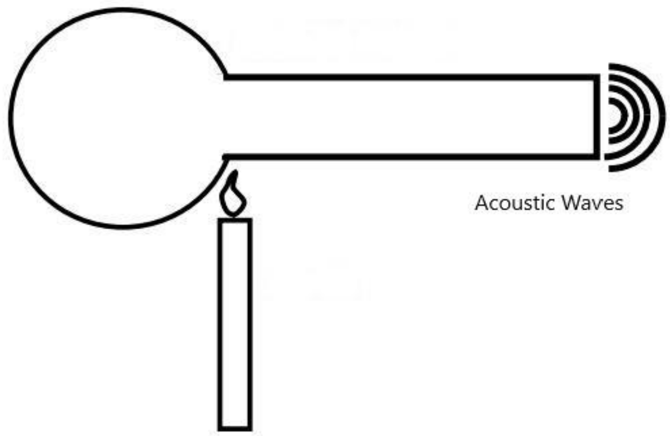

FIGURE 1: Physical illustration of Sondhauss apparatus

Cryogenics deals with the Taconis oscillations. The generation of Taconis oscillations occurs when tubes are closed from one end. However, the complete production of these oscillations happen when the open end of tube is dipped in helium (liquid form). In 1949, Taconis [9] was the one who observed this effect for the first time. The figure 1 shows the Sondhauss tube and Taconis oscillations are modified and extended form of the former one. The difference lies between these two experiments is that Taconis chilled the unblocked part of the tube. However, Sondhauss provided heat to the closed ending of the tube.

In early literature, the reliable theoretical groundwork regarding thermoacoustic effect is not present. However, Rayleigh [7] reported earliest findings about oscillations produced by heat in a gas column. Rayleigh noted that when gas is present and oscillating inside a tube, the movement enhances due to heat. The compressed stage for air is achieved when the pipe’s end which is closed is provided heat. Moreover, removal heat from the closed end takes the air into its minimum compressed phase.

In 1969, Rott [10-14] composed series of papers and these pieces of writings provided the framework about mathematical comprehensions of thermoacoustics. Rott’s work was about the derivations and solutions of linear equations. These mathematical derivations helped in providing the grounds for thermoacoustic theory. Current mathematical models of thermoacoustics are based on Rott's hard work.

Two well renowned experiments regarding "reverse effect" initiated further researches about this concept. Gifford and Longsworth [15] provided the demonstration in the beginning of these researches. They performed tests with the help of "low frequency pressure pulses." While performing experiments these pulses provide cooling effect within tube. The tube, which was used in the demonstration, was named as "pulse tube". Later on, the derivation of term "pulse tube refrigeration" occurred because of the "pulse tube". Later, the pulse-tube refrigerator was constructed by them.

The thermoacoustic influences while considering modified resonance tube were recorded by Merkli and Thomman [16]. They blocked the tube from one side and at the other side they placed sinusoidal driven piston. After running the system on resonance, temperature reduced and cooling effect was produced.

Moreover, LANL located in New Mexico investigated the effect of thermoacoutic cooling after studying the results of above-mentioned experiments. J. C. Wheatley and G. W. Swift put their efforts in these investigations. LANL have published several researches since 1980's until now. Swift [17] wrote a book comprised of significant information. Moreover, that book contained all fundamental theories of thermoacoustics. Following are some notable publications of Swift [18, 19, 20.]. Recently, wide range of researches has been done on thermoacoustic. Numerous experiments are being performed in research labs throughout the world. Swift is actively performing and demonstrating experiments (researches) on thermoacoustics at LANL. Moreover, swift is considered as active headman in the field.

1.2 Basics of Thermoacoustics

This section is about the introduction of thermoacoustic effect. The basic work background and operationalization about it will be discussed here. Moreover, chapter two provides the more detailed overview of this concept.

1.2.1 Change of Heat into Sound Waves

Production of pressured oscillation from heat is described by forward effect. The working of this phenomenon can be best described by assuming a tube filled with gas whose one side is blocked whereas, the other side is open as illustrated through figure 2.

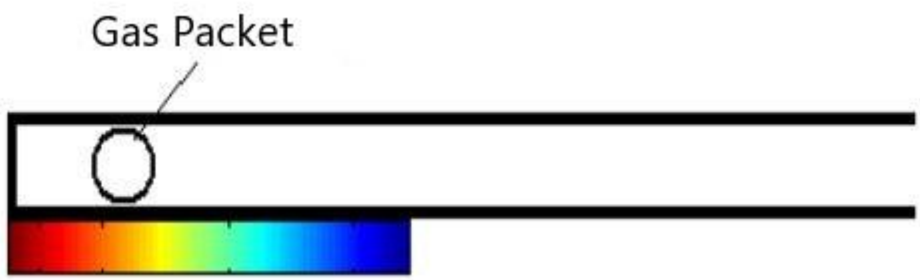

FIGURE 2: Thermoacoustic effect on gas

Figure 2 shows the spectrum of colors. The temperature gradient is associated with this color spectrum attached with wall of tube. The gas particle, at current placement, is less hot than the wall of the channel. Therefore, heat will transfer to the gas particle shown in Figure 2. The gas will expand because of heat. The left sidewall of the channel of gas particles is hotter than the right side. The gas on the left side of particle will become hot and expand more than it is observed. Moreover, the gas present on the right side of the particle will be less hot due to nearby sidewall is not very hot. The expansion due to heat will generate pressure gradient (from left to right). This pressure gradient will push all the particles of gas towards right side. After all these changes, the gas particle is now in different form and at new place.

The particle of gas has changed place and transferred to the other side. Close to the walls of the channel the particles of gas gets hotter than the walls. The difference in temperature made the gas particle to transfer heat to the wall of channel which as a result reduced the temperature of the gas. The particle of gas will contract after dispersing heat to the channel's wall. The contraction of gas particle will resemble with the contraction of remaining particles those moved because of temperature gradient. The displacement of particles creates pressure vacuum. The pressure vacuum triggers the particles of gas to travel once again to their original position as depicted through the Figure 2. This process continues.

The gas particles assumed a periodic type of motion. The procedure possessing four steps help in developing the understanding about thermoacoustic effect. Moreover, the detailed examples are mentioned in section 1.1. The repetition of process more than one time helps in the working at the open end of the tube. Engines (named as thermoacoustic engines in literature) are usually created by using forward effect.

1.2.2 Heat Pump with Acoustic Waves

Thermoacoustic refrigerator are created with the help of heat pumping by acoustic waves. This effect has few more applications. The forward effect deals with the thermoacoustic engines. However, the reverse effect is exactly the opposite of forward effect. The better understanding will develop of the process by looking at the illustration provided through figure 3 which is representing a tube blocked from one side whereas, the other side contains a piston which is moving.

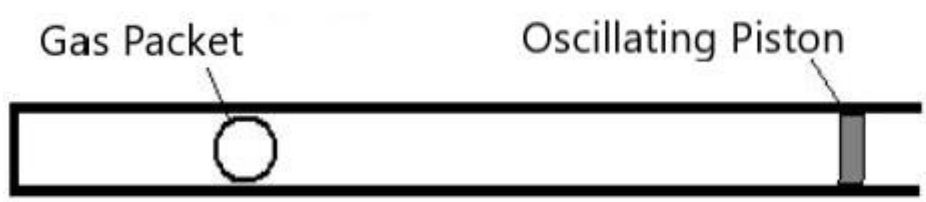

FIGURE 3: Gas in a closed resonator having a piston

Initially, gas is assumed to be static within the chamber. After the activation of piston, the process of refrigeration will take place. Sinusoidal operation of piston exists in current refrigerators. The process of four steps will be discussed here as mentioned in the prior section. When the piston will move towards left side, the air will also be forced to move with it. The air will be compressed because the piston moved and the volume of the tube is shrinking. This motion will change the alignment of the system.

The compressed gas particle could be seen when it had moved towards left. According to the ideal gas laws, the compression makes the gas particles hotter when they are at ambient temperature. However, the wall nearby remain at the ambient temperature. At this point, the heat moves from the gas to the wall. After the deposition of heat, the piston will move back to the right side of the tube. This will result into expansion of the gas.

The volume of the chamber increases when piston shifts towards the right side. The number of gas molecules remains same. Therefore, the expansion of gas occurs when piston moves to the right side. This results in producing the cooling effect of gas. The movement will cause the transfer of heat from the tube wall into the gas.

After some time, the gas becomes hotter due to back flow of heat. Moreover, during this process piston shift towards left-side again. After that, from initial step the process will restart. The quick advancement of the cycle transfers the heat from right to left. After some time, the development of temperature gradient will occur. This will cause pumping of heat with the help of gas.

In thermoacoustic engines, the maintenance of temperature gradient is primary for getting the output of work. Inculcation of work into the system is required for the maintenance of temperature gradient in thermoacoustic refrigerators. The examples as discussed above provide the conceptual knowledge to understand the underlying rules of physics about devices which are thermo-acoustic.

1.3 Present TAR Systems

Currently, no devices having thermo-acoustic effect are available in market. The thermoacoustic devices, which have been manufactured, are placed in educational institutes and research labs of government. This section deals with the review of some well researched thermoacoustic devices, which have been created.

Wheatly [19, 20] and his team, at LANL, manufactured first thermoacoustic device. This manufactured machine was useful thermoacoustic engine. Hofler [21] created first thermoacoustic refrigerator. He was also the member of Wheatly's team, who built first thermoacoustic engine. After some time at LANL, a thermoacoustic refrigerator, named as "beer cooler" was created [18, 22]. Instead of a speaker, a "heat driven prime mover" was utilized to drive this refrigerator.

An extension of Hofler's refrigerators design was created for the launch on the space shuttle discovery at "Naval Postgraduate School". The refrigerator was named as STAR (Space Thermo Acoustic Refrigerator) [23]. Adeff and Hofler [24] also built TADTAR (thermo acoustically driven thermo acoustic refrigerator) at "Naval Postgraduate School". In this refrigerator, the sunlight was focused with the help of a lens. Moreover, focused sunlight was utilized for the creation of heat. Therefore, this heat activated the working of thermoacoustic engine. The output form the engine was utilized by the refrigerator. Moreover, the refrigerator was operated by complete elimination of parts in motion. 2.5 Watts of cooling energy was attained by using the 100 Watts of input power from the sun.

SETAC (Shipboard Electronic Thermo Acoustic Chiller] [25, 26] was invented to cool electronics. It had the ability of performing at highest level. When comparing SETAC having maximum efficiency with the Carnot engine it appears that it possesses 21% COP. SETAC was designed for cooling the racks of electronics when operated at necessary power. Moreover, in relation with Carnot engine, 8% COP was achieved by SETAC

The name of the biggest thermoacoustic refrigerator ever built is TRITON. The name TRITON was given because it configured to provide 3 ton of cooling capacity air conditioner. TRITON is not enough researched. However, the information about it can be obtained by reviewing the Pennsylvania State University's website [26].

Tijani [27] conducted experiments to explore the influence of diverse parts of TAR systems. Taking into account his research findings he invented a refrigerator which produced the best 11% COP when comparing with Carnot. In this process as a working gas he considered helium.

Russel [28] created a cheap and inexpensive refrigerator possessing qualitative thermo-acoustic effects. Moreover, the making of this refrigerator was effortless. However, the working of this refrigerator was inefficient. It was created as an example of qualitative not for gaining the quantitative findings.

A project of inventing eco-friendly TAR was funded by an Ice Cream company who name is Ben and Jerry’s at Pennsylvania State University. Main purpose of making the refrigerator was to provide cooling for their freezers of ice cream [26, 29]. The capacity of cooling for this refrigerator was 119 Watts. Moreover, the coefficient of performance of this refrigerator is 19% relative to Carnot. Currently in Boston and Washington D.C., Ben and Jerry’s Ice Cream are using the prototypes of this refrigerator. The successful working of prototypes gives rise to the commercial production of TAR by this ice-cream company. Moreover, the Ben and Jerry’s Ice Cream want to exchange the clean technology in all their stores.

1.4 Scope of Current Thesis

Electromagnetic Loud Speakers are used in almost all of existing thermoacoustic refrigerators. These refrigerators are based on number of acceptable numerical models. Moreover, these models provide the powerful tool for engineers in designing motive. The high frequencies constrict the working of electromagnetic loudspeakers. Piezoelectric driver [30] solves this problem. Conventional loudspeakers have been avoided for the application dealing with magnetic sensitive apparatus. In comparison with “electromagnetically” driven counterparts, the “piezoelectrically” driven thermoacoustic refrigerators have no numerical models. A piezo-driven Thermo acoustic refrigerator is fabricated and experimented in this thesis.

1.5 Summary

The fundamental theories regarding thermo acoustics along with the brief literature review of thermo acoustic systems are described in the current chapter. The working principle of thermo acoustic engines and refrigerators are also discussed. The use of piezo-electric speakers instead of conventional loudspeakers is introduced and is also the topic of this research.

CHAPTER 2: THERMOACOUSTICS THEORY

Rott developed the initial mathematical model about the effect of thermoacoustic [10, 14]. Rott developed the linear model. Later on, Swift analyzed this model [18]. The current chapter accounts for the concepts of thermodynamic, fluid mechanics and acoustics. The derivation and explanation of equations about thermoacoustic effects depends on these concepts.

2.1 Thermodynamics Review

The field of thermodynamics considerably depends on the study of heat engines and refrigerators. The textbooks of thermodynamics include these topics in detail. Thermodynamics is considered as the core of thermoacoustic theory. The practical implications of the thermoacoustic effect can be seen as refrigerators and heat engines. The current section caters the principles of thermodynamics that are significantly related with thermoacoustics.

2.1.1 Thermodynamics first Law

Thermodynamics first law describes that energy creation and elimination is not possible but it can be altered from one state to an-other state. Change in the system's overall energy occurs due to the addition of heat in the system. In middle-of 19th century, heat was referred as the form of energy determined by joules [31]. Mathematically, the first law of thermodynamics is expressed as follows.

$$\delta Q + \delta W = dE \qquad (2.1)$$

The Eq. above reveals that "heat is system is represented by Q, work-done on system is represented by W and overall energy of system is represented by E".

The method of conduction is used for the transfer of heat for the thermoacoustic applications. The heat transfer rate is assumed as following:

$$\frac{dQ}{dt} = \dot{Q} = kA\frac{dT}{dx} \qquad (2.2)$$

The above equation shows that "thermal conductivity is represented by k, T is temperature and cross-sectional region is represented by A which is perpendicular to direction of x".

There are many sources of work done on the system. The two most widely used sources are mechanical and electrical work. However, the pressure-volume work is considerable importance in the study of thermodynamics and thermoacoustics. Moreover, there is an assumption that all forms of work are smaller than pressure-volume work. Therefore, every type of work is neglected in solving the thermoacoustic equations. Hence, the work done on the system is as follows:

$$\delta W = -p\delta V \qquad (2.3)$$

In the above equation, p is the pressure and V is volume. Reduction in the volume is caused by work-done on system. This results in making the δV as a negative quantity and δW a positive one.

2.1.2 Thermodynamics Second Law

The conservation of the energy is dealt by first law. Moreover, it does not deal with the energy transformations that will happen. The daily life experiences teach us that some energy transformations will occur and some will not. For example, the heat from a hot coffee cup can dissipate in the room environment but this process cannot be reversed. The example mentioned above doesn't disobey thermodynamics first law in either scenario. Moreover, the second law of thermodynamics necessarily explains the occurrence of types of specific energy flows and transformations (which particular energy flow or transformation will happen and which will not).

The scalar quantity "entropy" is a part of each system. Entropy deals with the useable energy within the system. The heat removal from the system causes the reduction in the entropy.

Similarly, the increment in the entropy of system occurs because of the addition of heat from the outside. The reversible processes within the system also increase the entropy. The insulated systems do not allow in or out heat flow in result of which systems entropy could increase or stays constant.

There are two categories of energy transformations, the reversible and irreversible transformations. To explain reversible energy here is an example. Moving ball when it is projected upwards, has a kinetic energy (K.E). Moreover, when a ball attains altitude the kinetic energy transforms into gravitational potential energy (P.E). The point will come when ball will be at rest, fully transforming kinetic energy into potential energy. After this, downward movement starts transforming P.E to K.E.

In the example above, the transformation of energy took place. Initially the kinetic energy was transformed into potential energy. Later on, the P.E converted into K.E. Hence, during all this system's entropy did not change.

In the irreversible processes, the transformation of energy occurs but some energy of the system transforms into less useable form. The concept of friction is a quite good example of irreversible process. For example, the sliding book on the table will produce heat, increasing the entropy. However, the energy of the system will remain same but the heat produced cannot transfer the book to its original place. This example explains the irreversible process and it cannot happen. If this happens, the system's entropy will reduced, disobeying thermodynamics second law.

Entropy of a system is represented by letter S. The exact value of entropy is not considered as a matter of interest. However, the basic concern is about how the entropy alters. Hence, the entropy change is represented by following expression.

$$dS = \frac{dQ}{T} + (dS)_{gen} \qquad (2.4)$$

Where As:

$$(dS)_{gen} \geq 0 \qquad (2.5)$$

The closed system is depicted by above equations. The open-system deals with the inclusion of additional terms that is mass. Following is open-system form for the Eq. (2.1).

$$\delta Q + \delta W + \left(h + \frac{|V|^2}{2}\right) dm = dE \tag{2.6}$$

In the above equation, h indicates the enthalpy "(a sum of internal energy along with the pressure time volume)". Velocity of the small mass particle is represented by *v*. Moreover, the mass that flows across the boundary is designated by dm. Therefore, the equation for the open system (2.4) becomes as follow:

$$dS = \frac{dQ}{T} + sdm + (dS)_{gen} \tag{2.7}$$

2.2 Fluid Mechanics Review

The thermoacoustic devices contain gas, usually referred as working fluid. Moreover, within the thermoacoustic device, gas oscillates. The better interpretation of the physics of the fluid will help in the development of better understanding of the thermoacoustic effect. Thermoacoustics deals with the two significant equations from the fluid-mechanics and those are *"equation of continuity"* and *"equation of Navier-Stokes"* as discussed below.

2.2.1 Equation of Continuity

The primary assumption of the continuity equation is conservation of mass within any control volume of fluid. The difference between the quantity of the fluid moving into and out of the control volume, results in the alteration of the amount of mass in a fixed control volume. The equation transforms as follows:

$$\frac{\partial \rho}{\partial t} + \nabla + (\rho v) = 0 \tag{2.8}$$

The equation (2.8) $\frac{\partial \rho}{\partial t}$ represents the change in density in relation with time and for small volume. Moreover, (ρv) indicates the fluid's mass-flow at the small volume.

2.2.2 Equation of Navier-Stokes

The newton's second law for fluids is described by the equation of Navier-Stokes in which ignoring viscosity is not possible. The sum of forces on a system is equal to time rate of change of momentum is described by Second Newton's Law. The equation for viscous-fluids is as follows:

$$\rho\left[\frac{\partial v}{\partial t} + (v.\nabla)v\right] = -\nabla p + \mu\nabla^2 v \qquad (2.9)$$

Equation (2.9), the left hand side shows the "density times the acceleration". The temporal and special acceleration are the two components of acceleration. On the right hand side, the forces acting on the small volume are indicated in the above equation. First term deals with the pressure gradient. The viscous shearing force deals with the second term. There are many other thorough equations for the momentum of fluids but the Navier-Stokes equation is a detailed one. The equation of Navier-Stokes is more than enough and used in the current research for the explanation of applications of thermoacoustics.

2.2.3 Thermodynamics Law (for Fluids)

On the control volume (C.V) of fluid we can apply the thermodynamics first law. This law expresses that in the control volume total energy is sum of the internal and kinetic energy which mathematically can be expressed as:

$$(\rho\varepsilon + \tfrac{1}{2}\rho|v|^2)dxdydz \qquad (2.10)$$

In the equation above, the internal energy is represented by ε. Thermodynamics first law describes that variation in energy corresponds to the combined effects of work-done on system, the heat which enters into the system and loss and gain of energy due to flow of mass which enters and leaves the C.V.

Following is the equation of energy about the C.V of fluid according to the first law of thermodynamics:

$$\frac{\partial}{\partial t}\left(\rho\varepsilon + \tfrac{1}{2}\rho|v|^2\right) = -\nabla.\left[-k\nabla T + \left(\tfrac{\rho}{2}|v|^2 + \rho h\right)v + v.\sigma'\right] \qquad (2.11)$$

In the above equation, the left-hand-side term is a rate of change of Eq. (2.10). In the Eq. (2.11), the first term represents the conduction of heat into the control volume. The work done on the control volume is indicated by next term. Whereas, the σ' shows the stress tensor for the fluid. The total energy flow because of the crossing of mass into the control volume is represented by the terms within the circle brackets and the terms that they multiply.

2.2.4 Ideal Gas

The working fluid present within the thermoacoustic refrigerator or engine are generally referred as ideal gases. The ideal gases go after some significant and renowned relations that are as follows:

$$p = \rho RT \tag{2.12}$$

$$c_p = \frac{R\gamma}{\gamma - 1} \tag{2.13}$$

$$C_v = \frac{R}{\gamma - 1} \tag{2.14}$$

The ideal gas law is represented by the equation (2.12). The equation (2.13) shows the constant pressure of specific heat. The constant volume specific heat is indicated by the equation (2.14). The constant of gas denoted by R for a gas having negligible viscosity corresponds to the ratio of constant of universal gas and fluid's molar mass. The ratio of specific heats is represented by γ which is depicted by the combination of (2.13) and (2.14) equations. Also it is equivalent to proportion of specific heat at constant pressure and volume.

2.3 Summary

In this portion of thesis, basic principles of thermodynamics and fluid mechanics are discussed briefly that how they are applied to thermo acoustic devices for their better performance and working.

CHAPTER 3: DESIGN OF THERMOACOUSTIC REFRIGERATOR

In the field of thermo acoustic Refrigerator, a great deal of research is now being done. This writing contains numerous continuous discussions with regards to what the best design procedures might be. This section begins with a basic structure technique for thermo-acoustic Refrigerator, and afterward proceeds to talk about the parts in detail, keeping in view the Literature view.

3.1 Overview of Design

There are four sections of Thermoacoustic refrigerators. The figure displays the four parts of the refrigerator namely, the driver, resonator, stack and heat exchanger. The arrangement for a typical thermoacoustic refrigerator is shown above. There are various thermoacoustic refrigerators in presence, some of them do not even look like the below-mentioned refrigerator appeared in the figure 4.

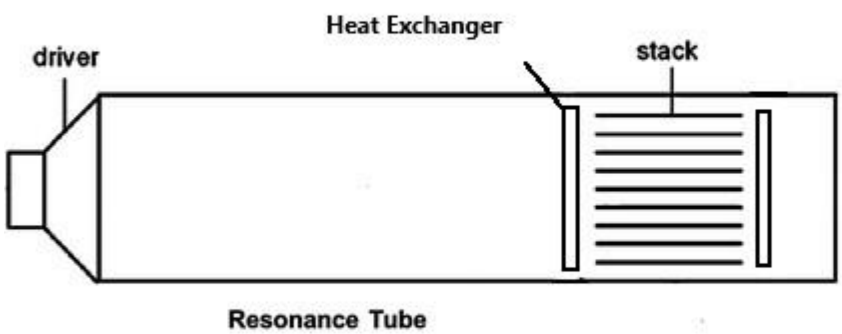

FIGURE 4: Thermoacoustic Refrigerator Parts

In the Thermo-acoustic refrigerator, the driver makes either a standing or travelling wave inside resonating tubes. The wave made by the driver is mostly on or close to the resonant frequency of the resonator in which the wave moves. The stack is situated sooner or later inside the resonator tube and used to make excessive surface-area across which the thermo-acoustic impact can happen. At long last, the heat exchangers are utilized to take heat from a refrigerated area and remove it to the outside. The detailed description of each part is presented in further sections.

Russel [28] portrayed a modest and simple way for the making of thermoacoustic refrigerator. The refrigerator is perfect for the exhibition as its working is inefficient. On the other hand, it is a magnificent beginning stage for those inspired by the field.

Tijani [32] has written a detailed paper about designing a thermoacoustic refrigerator from the beginning to end. He begins by planning the stack to have the option to fulfil the basic cooling features. The configuration of the stack depends on the pressure, frequency and the working fluid. When the finalization of previous factors is done then material, parameters and position of the stack is planned. The design of the resonator depends on the limitations of the natural frequency and limiting loses at the enclosure.

The heat exchangers are then planned however the writer accepts that very little is thought about heat exchangers in oscillatory systems with zero mean displacement. Then the last component of the refrigerator to be designed is acoustic driver. Tijani [33] depicted in detail about the construction and fabrication of the refrigerator's elements.

While trying to enhancing the thermoacoustic refrigerator design, Wetzel [34] built up a calculation for design optimization of thermoacoustic refrigerators. The created calculation divides the optimization procedure into the four fundamental parts already mentioned above. Detailed explanations have been provided about the maximization of the stack and resonator. However, the explanations catered the issues about the heat exchanging mechanism of the thermoacoustic refrigerators that are known by few. Moreover, the improvement of the driver is a separate problem that has a long history other than the thermoacoustic refrigerators.

3.2 Parts of Refrigerator

Concentrating on the overall structure of a thermoacoustic refrigerator can be difficult. It's a lot simpler to inspect the various parts of the structure exclusively. This area surveys the study about the different components of thermoacoustic refrigerators exclusively.

3.2.1 Driver

The driver is responsible for the acoustic waves within a thermoacoustic refrigerator. Usually in the thermo-acoustic refrigerators, the electro-magnetic loudspeakers work as driver. However, different kinds of drivers can be utilized. Where high frequencies are required Piezo-electric speakers are utilized. Adeff and Hofler [24] utilized thermo-acoustic engine while working on TADTAR. Oscillating piston is used by Reid and Swift [35] in one of their design.

At the Pennsylvania State University an investigation for selection and design of electro-dynamic drivers for TAR System was done by Wakeland [36]. Despite the fact, Wakeland accepts that during investigation of driver's parts, not all of them were considered, but he concluded four points. First point of Wakeland is that the proportion (Bl) 2/(ReRm ought to be increase where L represents the length of coil, the coil's inductance is depicted by B, the driver's electrical resistance is Re and RM is the mechanical resistance of the driver.

Second decision is about the rigidity in the driver's suspension ought to be pick in order to build the collective impedances of mechanical and electrical that is totally genuine for the working frequency of the TAR system. The decision was made that by choosing a piston size the electroacoustic efficiency ought to be increased; therefore, matching the impedance between the mechanical and acoustic load happens. Wakeland's last decision is about situation in which the driver cannot be changed. The working frequency can be balanced in order to accomplish matching impedance in such cases.

Working of Wakeland's second decision, Tijani [37] built up a strategy to effectively control the mechanical impedance of the speaker in order to genuinely build the joined system's electrical and mechanical impedance. Varying volume of the gas had the fixation with the rear of speaker. The volume of gas on the speaker's diaphragm generates a spring force and it is volume's function. The imaginary part of complete impedance was removed by changing the volume and the maximum efficiency happen for this case describes by Tijani.

Li [38] builds up a PI control Algorithm to manage the operating frequency of thermoacoustic drivers. During the transient phases of operation this frequency can change since the natural frequency of the TAR system is responsible for the sound speed in fluid that varies as the temperature fluctuates. Li and his associates created a controller that estimates both the acoustic and electric powers. This controller tries to maximize the efficiency that is characterized as the acoustic power output against the electric power input.

Li et al [39] broaden the working by the incorporation of a piston at the rear of resonator. This incorporation makes the size of the resonator as another changeable variable alongside the frequency of the speaker. The basic purpose of the design was to enhance the power of the cooling. It was revealed that the controller can locate the optimize frequency of the driver and size of the resonator. This also modifies the varying circumstances within the thermo-acoustic refrigerator.

3.2.2 Resonator

The resonator in a thermoacoustic refrigerator deals with the containment of the working fluid so that it achieves a desired natural frequency. Resonators are commonly of two types, half or quarter wavelength resonators. Resonators which are quarter wavelength are constructed with tubes by closing one end and making the length around one fourth of the required resonant frequency wavelength. A large volume is attached at the end to stimulate the open end of tube. By attaching large volume a boundary condition of zero pressure is generated at the end, creating the tube's end velocity anti-node and pressure node. Whereas pressure antinode and velocity node is created approximately at the start of the tube. This shows that such resonators natural frequency wavelength is four times the resonator length.

Half wavelength resonator is a long tube whose one end is closed. The closed end implies that there is no movement of gas inside the resonator, making a velocity node and pressure anti node. The driver at the start of the tube also makes a velocity node and pressure anti-node so that natural frequency of the cavity becomes half the acoustic wavelength.

The actual thermo-acoustic resonators are commonly near to half or quarter wavelength resonators yet are not accurate. The reason behind is that the ideal resonators are difficult to fabricate and are not generally the most ideal decision as is currently examined. Likewise, the supposition that is velocity pressure anti node was assumed according to driver. The authenticity of this supposition is a driver's function and it's joining with the resonator.

Inertance in TAR systems was discussed by Gardner & Swift [40]. They noticed that when the acoustic impedance is completely real, maximum acoustic efficiency will happen. Numerous refrigerators have a huge tank with the resonator which produces negative imaginary component of impedance. To counter this phase shift, inertance can be utilized to establish a positive imaginary part for the impedance and make the impedance real. The revision of Wakeland's work in the previous section that the overall impedance of the driver's connection with the resonator is truly what ought to be analysed. In this manner, utilizing inertance is an alternate instrument for tuning of the general impedance to be simply real. However, it ought to be balanced with driver's coupling.

Tijani [32] noticed that the acoustic power loss and surface area of the resonator are proportional to each other. The surface area is around half in comparison to half wavelength resonator and will be extra efficient for a quarter wavelength resonator. He additionally takes note that the endpoint of the tube, the point where change to the large volume happens in a quarter wave length, the resonator can create drops because of turbulence created by the sharp changes. He suggested a solution to this problem that a cone shape to buffer the volume. He observed 9 degree of ideal half angle of tapering.

Hofler [41] describes that the diameter of the tube can be reduced where we have no requirement for the stack in a resonator tube. In this way, the little diameter tube lessens the losses which are relative to surface area of resonator. On the other hand, as the second tube's diameter is reduced as compare to first one, the viscous losses will be reduced and the thermal losses will increase.

Tijani [32] state that the ideal proportion for second tube is 0.54 times the diameter of first tube. He on the other hand recommended that cone shaped between the two tubes avoid turbulence. At last, Tijani states that the linear tubes have frequencies that are harmonic. In the event where nonlinear impacts emerge, they will regularly energize these higher harmonics if straight tubes are utilized. In this manner, straight tubes are the least difficult resonators they are mostly less efficient. The resonator's configuration by Tijani brings the impacts in this account is shown in the below Figure 5.

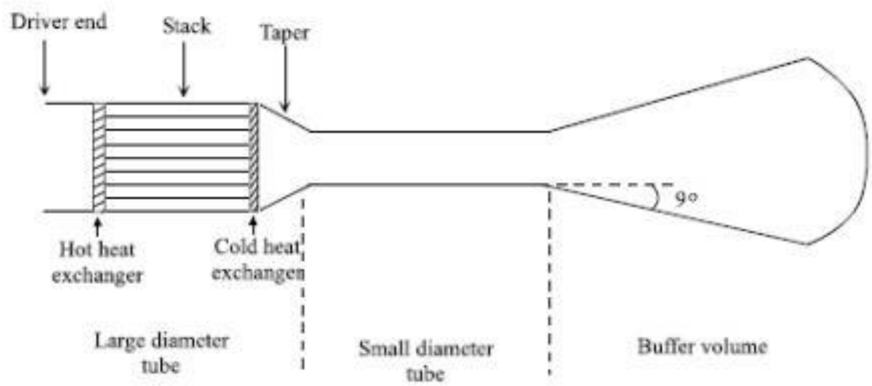

FIGURE 5: From [32], Optimal Resonator for Thermoacoustic Refrigeration

3.2.3 Stack

Thermoacoustic refrigerator's heart is known as "Stack". The stack is the part where thermoacoustic effect takes place. The stack is considered as a most receptive part that any change in dimensions of stack results in alteration in performance.

The achievement of the engineering field deals with the design of the stack that caters the balance between the cooling power and efficiency. The tradeoff depends on the position in the resonator where oscillations of velocity and pressure interact together to have the maximum thermoacoustic effect. This is the small cross section area, in which there will be no cooling effect if it were not for the stack. The decrease in efficiency and increment of the cooling effect depends on the length of the stack. Tijani et al. [32] proposed that there is an optimal placement for every stack length. The optimal placement is at the closure to the mid-way through the pressure and velocity nodes.

The stack design depends on the important aspect that is stack spacing. The increment of the power density is based on the increase in the surface area of the stack because surface area is the place where thermo-acoustic effect occurs. Moreover, if there is increase in surface area's density, the thermo-acoustic effect will ultimately stop because of powerful thermal connection among the stack and working fluid. Optimum gap between stack is explored by Tijani et al [42] for plates which are parallel by comparing various gap dimensions for stack. Later on, it was revealed that the optimum spacing for the refrigerator was 2.5 thermal penetrations.

Moreover, while taking in account of the stack's design, the stack material and thickness are important. The suitable material is with low thermal conductivity because heat conduction across the stacks act opposite to the refrigerator. However, heat capacity of the material should be more than that of the working fluid so that the temperature gradient is generated and stays. The material examples mentioned in the literature are Mylar [42] and 35mm camera film [43].

The material thickness must provide enough heat capacity and the thickness should cut down by keeping in mind to lessen the hindrance because of the stack plates. The other drawback of the increase thickness of the stack is the emergence of eddies at the stack's ends that results in losing. A computational-model was given by Blanc-Benon et al. [44] for flow at the end of thermo-acoustic stack and validated the findings through measurements of PIV. This working revealed that as the thermoacoustic stack thickens this result in the formation of eddies.

3.2.4 Heat Exchanger

The sufficient amount of literature exists about the heat transfer under constant flow. Without average displacement of particles of gas, there is an oscillatory movement inside the TAR system. Peak et al. [45] proposed that on the topic of heat transfer under these circumstances limited research has been done. The researches were performed with focus on thermoacoustic refrigerators.

Copper is normally used for the manufacturing of heat exchangers and heat exchanger usually resembles with the stack's cross-sectional profiles. For better flow the stack's porosity and heat exchanger's porosity should match as suggested by Tijani et al, [32]. Moreover, the heat exchanger's length should be in place with the gas particle's maximum displacement.

A heat exchanger was manufactured by Nosfar et al, [46] whose shape resembles to parallel plate stack. He did the fabrication and testation of the model of heat exchanger. The results of their experiments had flaws and did not follow the theory accurately. There was an assumption that the coefficient of heat transfer is high because of the more gas particles are being in contact with the surface of heat exchanger.

3.2.5 Working Fluid

While making the design, selection of best working fluid for resonator is another significant thing. Belcer et al. [47] noticed the best characteristics choice for working fluid is high proportion of specific heat and small Prandtl number. A smaller Prandlt number indicates the small viscosity changes in comparison with temperature changes.

This idea was investigated by Belcer et al. [47] in more detail. Belcer et al. [47] proposed that in a mixture of two gases, when the lighter gas is 66% by volume approximately, the minimum Prandtl number is obtained. Moreover, he also suggested that the importance should be given to the design application in the selection of fluid for thermoacoustic devices. He simplified the concept by giving the following example that when the design goal is small differences in the temperature, then mixtures of the gases which are polyatomic with less certain proportions should considered.

Tijani et al, [48] worked with number of varied gases in the acoustic refrigerators as working fluids. The main focus of the experiments were on mixing the helium with other noble gases and observing the resulting Prandtl numbers influencing the working of the refrigerators. The study revealed that when the fraction of moles of helium with noble gas decreases, Prandtl number also decreases but working fluid’s density increases. The increment in the working fluid’s density results in the reduction of the system’s cooling power. All of this results in the compromise between efficiency and cooling power. At the end, it was concluded that the optimum working fluid for helium-noble gas mixture is dependent on the specific design of the refrigerator. At the end, it was concluded that optimum mixture of working fluid is dependent on design specification.

The procedure for the calculations of thermal conductivity, viscosity and Prandtl number for mixture of gases was presented by Giacobbe, [49]. Validation for the theoretical work, his paper contains the experiments including the combinations of helium and the rest of noble gases.

The results of these experiments are identical to the theory proposed by him. Therefore, to get the reasonable guess of Prandtl number for mixture of gas, this technique is used.

3.3 Summary

In this chapter, some basic design techniques are described for thermo acoustics refrigerators. The essential design features of all the components and their effect on the performance of thermo acoustic refrigerators are also discussed.

CHAPTER 4: PIEZO-DRIVEN THERMOACOUSTIC REFRIGERATOR

In this chapter we discuss the design decisions for the components of Piezo-driven Thermoacoustic Refrigerator as well as their fabrication. Then we discuss the working operation of this refrigeration system along with the experimental results. The aim of the study is to investigate the best suitable stack parameters for thermoacoustic refrigerator system as well as the materials choice for stack.

4.1 Design of Thermoacoustic Refrigerator

The driver's choice was the beginning of TAR system as we were using piezo-electric speaker as a driver source. After selecting reasonable driver for our refrigeration system, the decision of the resonator and stack will be discussed.

4.1.1 Selection of Piezoelectric Driver

Usually piezoelectric speakers contain diaphragm made up of metal along with stored material on it which is piezo-electric in nature. Piezoelectric material is joined with electrodes from both sides. The piezoelectric material expands and contracts when voltage is applied but metallic diaphragm isn't get influenced which causes bending moment in the diaphragm. The to and fro movement of diaphragm due to applied voltage causes the surrounding air to oscillate. This type of speaker is shown in the figure 6.

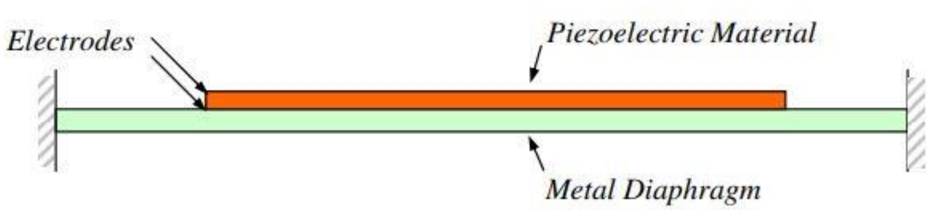

FIGURE 6: Piezoelectric Speaker

As compare to electromagnetic loudspeakers, piezo-electric speakers yield extensive sound generated power when the frequency is high. So a common piezoelectric speaker is used for this thermoacoustic refrigerator.

4.1.2 Design of Stack

The efficiency and performance of thermo-acoustic system depends on the variables like length of stack, porosity, position of stack and frequency. The biggest challenge is selection of material and satisfactory parameters of stack. Camera film, Mylar, Stainless steel and Aluminium foil are the usual choices for the stack. The parallel-plates, honey-comb, corning-celcor, spiral and pin-array are the components of stack type shown in figure 7.

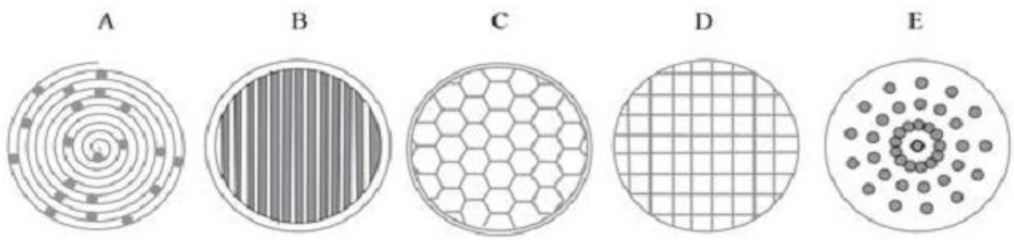

FIGURE 7: Stack geometries A. spiral-stack, B. parallel-plates, C. honey-comb, D. corning-celcor, E. pin-array

Many sheets wrapped around the rod and this makes up the spiral stacks. The composition of common spiral stack depends on the camera film or Mylar sheets cloaked around the fishing lines. The gap between layers is from two to four times the depth of thermal penetration. The equation to find depth of thermal penetration is given below:

$$\delta_k = \sqrt{\frac{k}{\pi f \rho c_p}} \tag{4.1}$$

Where k is the thermal conductivity of air at room temperature, driving frequency is represented by f, density of air is represented by p, cp is specific heat capacity while depth of thermal penetration is represented by δ_k. Air is the working fluid for our TAR system which is at room temperature. Following are the properties of air at room temperature used in 4.1.

$$\text{Thermal Conductivity } k = 0.0257\frac{W}{m\,.K} \tag{4.2}$$

$$\text{Density } \rho = 1.205\frac{kg}{m^3} \tag{4.3}$$

$$\text{Specific Heat Capacity } c_p = 1005 \frac{J}{Kg.K} \tag{4.4}$$

The above variables are then substituted in Equation 4.1, which results as follow:

$$\delta_k = 1.316 \times 10^{-4}\ m \tag{4.5}$$

The stack spacing should be around two and half times the depth of thermal penetration as mentioned in chapter 3. So the final stack spacing becomes 0.329 mm. A spiral cross section is defined for the stack. In order to enhance volumetric and pressure flow rates in the resonator, the cross section of stack is chosen to be smaller than the diaphragm of speaker.

4.1.3 Design of Resonator

The design of resonator was according to the diameter of stack and size of the diaphragm of the piezo speaker. So its manufacturing was easy and it was made up of simple acrylic tube. According to dimensions of speaker one side of resonator-tube was bigger while the opposite side is smaller and closed with the cap of aluminium because this side is the hotter side of refrigerator. The cap of aluminium is used because aluminium will assist the system to remove heat.

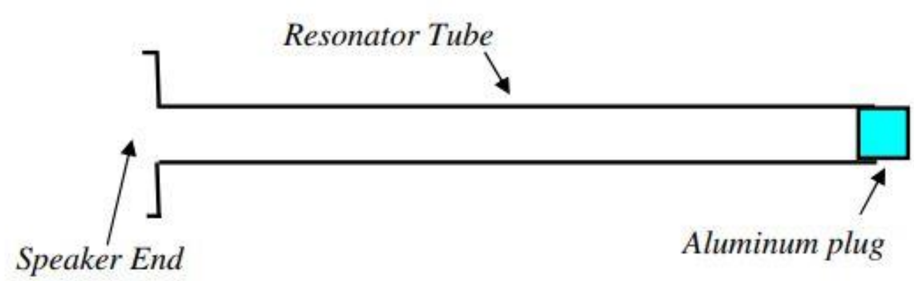

FIGURE 8: Design of Resonator

A Quarter-wavelength resonator is shown in above figure because velocity node and pressure anti-node is at the aluminium cap end whereas velocity anti-node and pressure node is at the other end approximately. Calculation for resonator length is as follow:

$$L = \frac{velocity}{4f} = \frac{343}{4 \times 395} = 21.7cm \tag{4.6}$$

The final resonator length is 22 cm after the test experiment and the frequency become 390 Hz. This variation is due to the boundary condition at drivers end. The diameter of resonator tube is equal to the diameter of stack which is 1 inches and for optimal stack length and position several experiments were performed for efficient cooling.

4.2 Fabrication of Thermoacoustic Refrigeration system

The resonator was made up of acrylic tubes, while the driver was bought from the market. DHT sensors were used to measure the temperature across stack material. Whereas for stack three different materials were tested which are Camera film glued with fishing lines, Aluminum foil glued with fishing line and steel wool.

4.2.1 Fabrication of Stack

A spiral shaped stacks were made using three different materials. Fishing lines glued with stack to ensure the spacing between the layers to create thermal penetration depth as shown in figure 9. The camera film and aluminum foil is rolled in spiral shape once the glue is dried as shown in figure 10. Stack for all the three materials can be seen in figure 11.

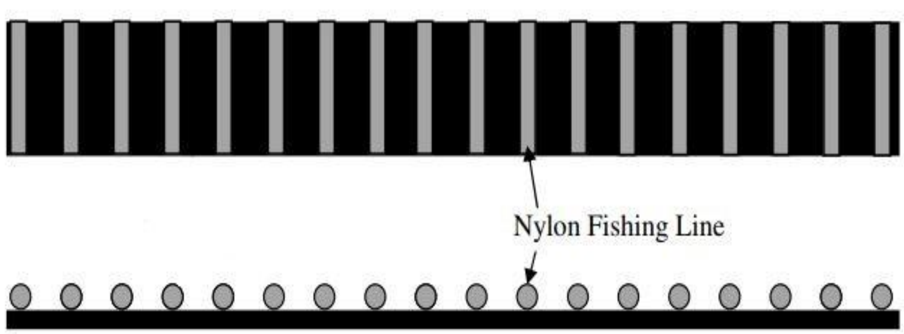

FIGURE 9: Stack glued fishing Lines

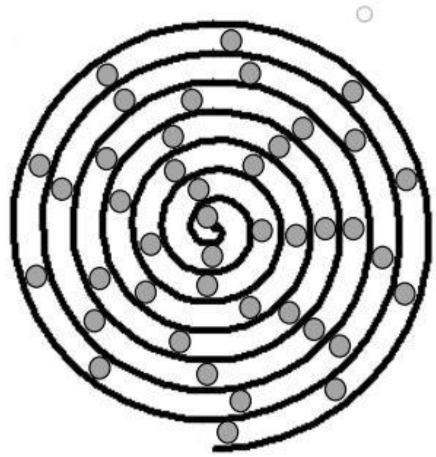

FIGURE 10: Rolled up Spiral stack glued with fishing lines

FIGURE 11: Stack made up of three different materials

4.2.2 Fabrication of Resonator

An acrylic tube was used for the fabrication of resonator whose length is 22 cm and inner diameter is 1 inches. An aluminum cap is fixed at one end while the speaker is fixed at the other end of the tube. Two holes were made inside the resonator tube for installation of temperature sensors across the stack. Once the sensors are placed, glue is used to seal the holes to avoid leakage. Assembled form of resonator is show in the figure 12.

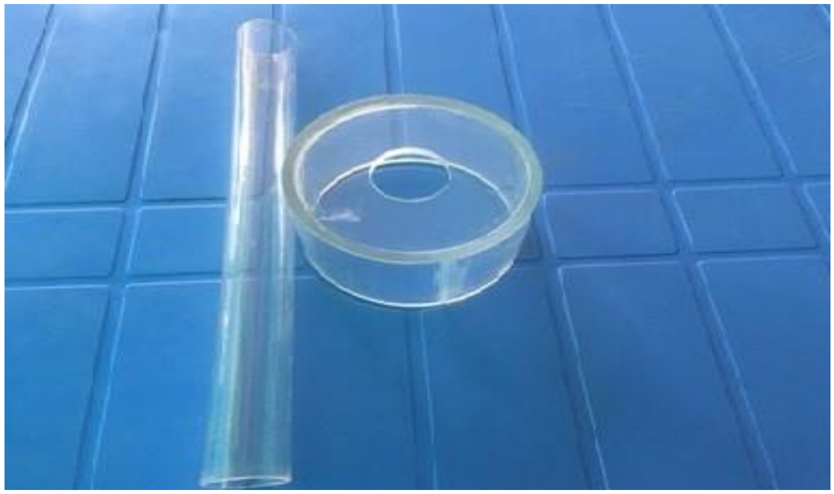

FIGURE 12: Assembly of Resonator

4.3 Operational Setup

The aim of the study is to investigate the working of geometrical stack parameters in a TAR system as well as the materials choice for stack. Therefore, no heat exchangers are used in the current experiment. The two adjacent acrylic tubes comprise the resonator. The first tube can fit on the face of the speaker. The other one is small that it fits on the stack. The stack is in the spiral shape made up of Camera film, steel scrap and Aluminum foil. A nylon fishing line is attached to the film. The film is rolled up in spiral shape and glued at the end to form the stack porous body. A rigid aluminum plug closes the resonator. An amplifier drives the piezo-speaker. The speaker, from a function generator, receives the input voltage signal. The programming of the electronic board was done for the production of sound waves input to the piezo-speaker. The current experiment deals with the sinusoidal wave function. The enhancement of the magnitude of sound pressure carried out by amplifier. For the measurement of input voltage and input power, the multi-meter was used. The, 6W, input power was provided to the loud speaker. For the measurement of the hot and cold temperatures, two temperature sensors were attached on each side of the stack. The setup of experiment and schematic diagram for setup of Experiment is shown in figure 13 and 14.

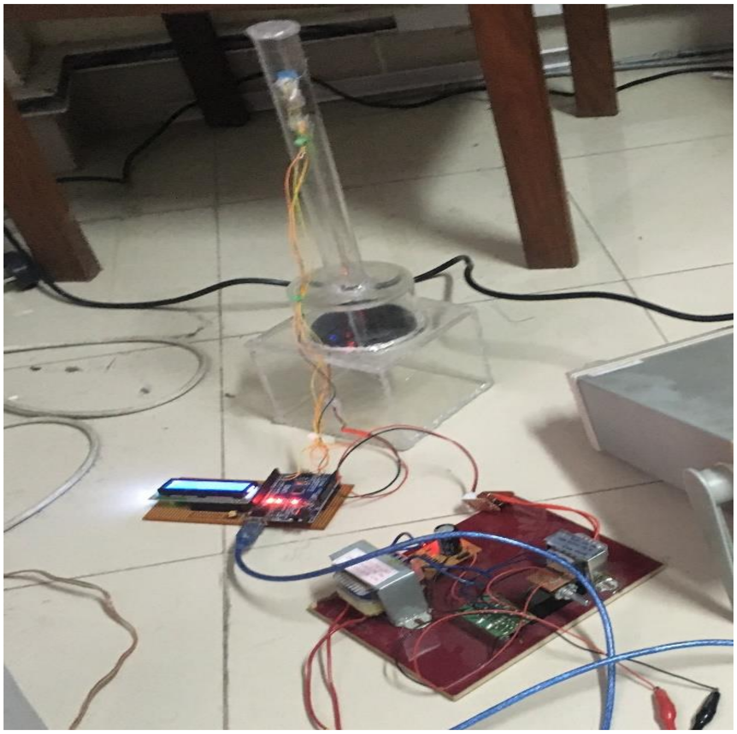

FIGURE 13: Setup of Experiment

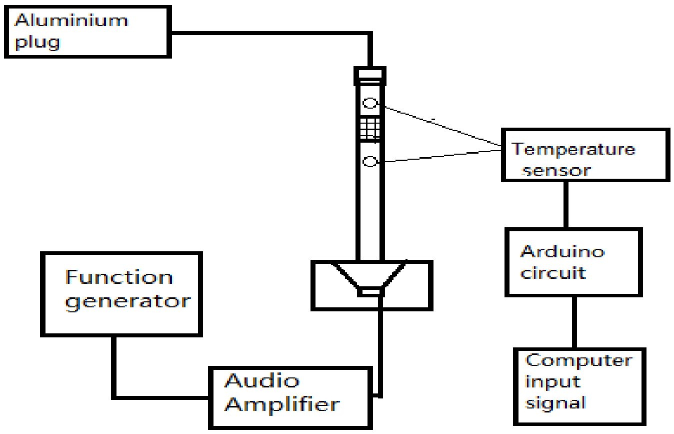

FIGURE 14: Schematic Diagram for Setup of Experiment

4.4 Summary

In this chapter design detail of all the components of piezo-driven thermoacoustic refrigerator is discussed along with their fabrication details. After the details discussion of design and fabrication, complete operation of thermoacoustic refrigeration system is described.

CHAPTER 5: RESULTS AND DISCUSSION

In this chapter the results of thermoacoustic refrigerator setup are discussed in detail. The main objective of these experiments was to discover the optimal length and position of stack and to find the best suitable material for stack.

5.1 Results

Initially, the length of the stack was 180mm and position was of 400 mm from the closed end. The experiment prolonged for thirty minutes. During the experiment, 390 Hz frequency was used for each case by changing the length and position of the stack as shown in the table 1.

Table 1: Stack Length and Position Optimization

Stack Length (mm)	Stack Position (mm)	Maximum Temperature Difference (°C)
180	400,350,300,250,200,150	6.5
150	400,350,300,250,200,150	7.5
130	400,350,300,250,200,150	8
100	400,350,300,250,200,150	9
70	400,350,300,250,200,150	8.5
50	400,350,300,250,200,150	7

After discovering the optimal stack length and stack position. Experiments are conducted to obtain the best suitable material from all the three materials. Results showed that Aluminum foil glued with fishing lines gave more cooling effects as compared with the camera film and steel scrap at same working conditions as shown in Table 2.

Table 2: Time vs Temperature Difference

Time (minutes)	Temperature (°C) Camera film	Temperature (°C) Aluminum foil	Temperature (°C) Steel scrap
0	38	38	38
3	37.5	37.5	38
6	37	37	37.5
9	36.5	36	37
12	36	35	36
15	35.5	34	35.5
18	33.5	33	35

21	33	32	34
24	32.5	31	33.5
27	31.5	30	33
30	31	29	33

The figures 15 show the findings of thermo-acoustic refrigeration system with different lengths and positions of stacks for camera film. The numbers of experiments were done for finding out the optimal range of length and position of stack. The maximum difference of temperature has shown by red region and the minimum is shown by the blue region. The discovery of optimal length and position of stack was the main purpose.

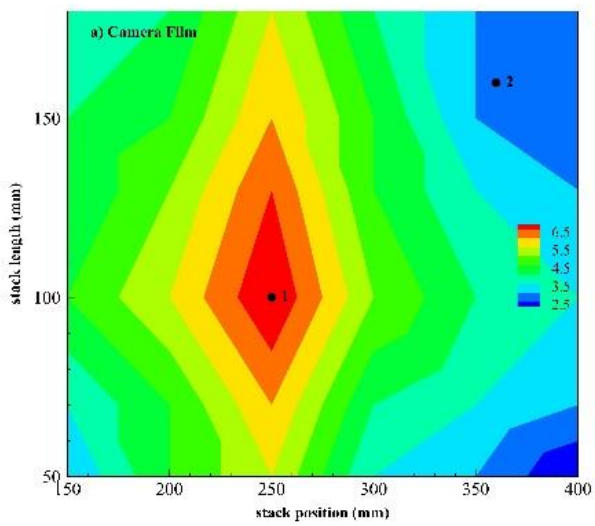

FIGURE 15: Optimum stack length and position for camera film

After that experiments were conducted for Aluminum foil glued with fishing lines to find the optimal range of stack length and stack position for thermo-acoustic refrigeration system and the results for optimal stack length and stack position for aluminum foil glued with fishing lines was very much close to camera film as shown in figure 16.

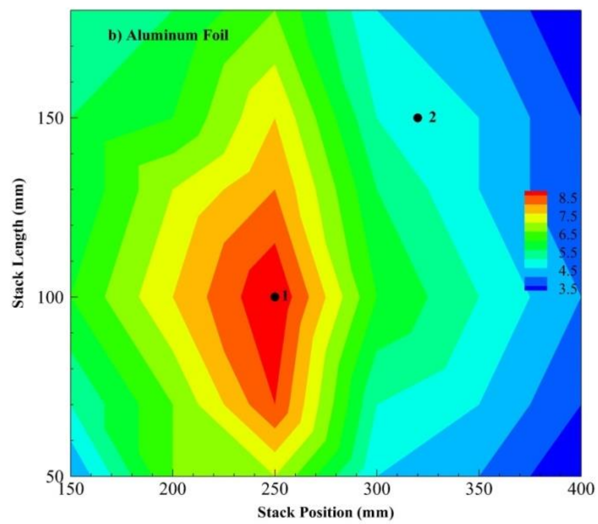

FIGURE 16: Optimum stack length and position for Aluminum Foil

Similarly experiments were conducted for Steel Scrap to find the optimal range of stack length and stack position for thermo-acoustic refrigeration system and the results for optimal stack length and stack position for Steel scrap was very much close to camera film and Aluminum foil as shown in figure 17.

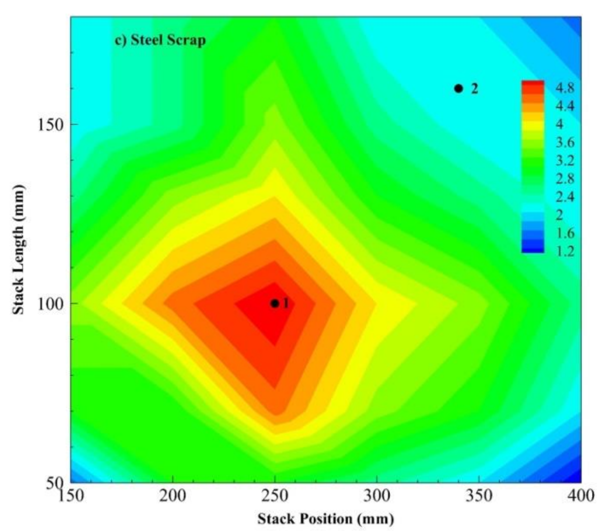

FIGURE 17: Optimum stack length and position for Steel Scrap

After the completion of experiments for stack length and stack position, it has been observed that cooling effect is produced when stack moves closer to the closed end of the resonator. Moreover, categorically, the maximum difference in temperature was observed when length of stack is 100 mm and position of stack is 250 mm for our thermoacoustic refrigeration system.

After knowing the optimal length and position of stack, experiments were done by using three separate materials of stack. The results revealed that the aluminum foil rolled up with fishing lines in comparison with the camera film and steel scrap produces maximum cooling effect. The figure 18 reveals the difference of 9 degrees temperature during the experiment.

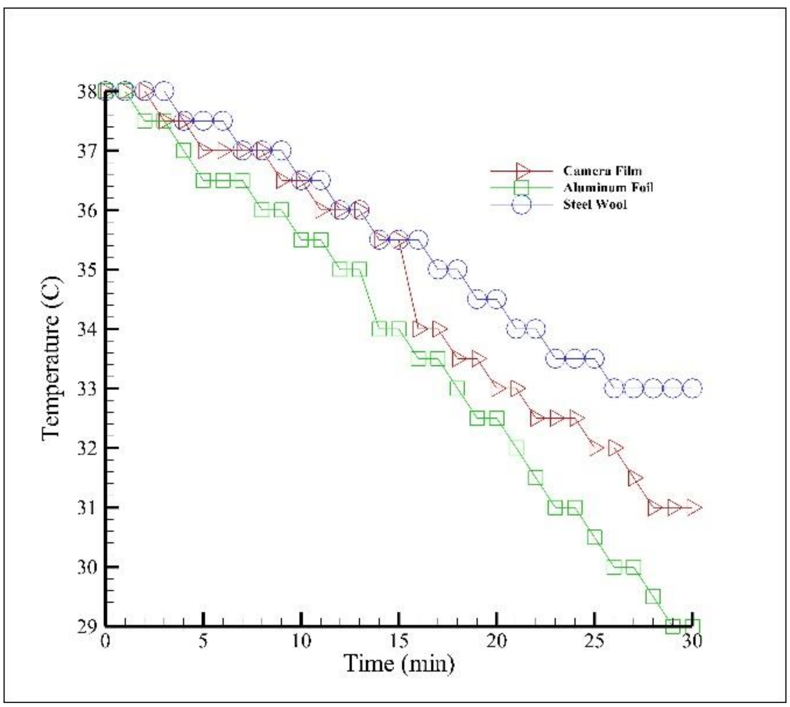

FIGURE 18: Comparison of different stack materials

5.2 Conclusion

The current paper focused on the geometrical investigation of stack material such as stack length, stack position and working of thermo-acoustic refrigerator by using piezoelectric loudspeaker. There are important factors like choice of material of stack and manufacturing of stack influencing the efficiency of thermo-acoustic refrigerator (TAR). The sustainability is the major attribute of TAR. The study of working of TAR depends on the geometrical configurations like porosity, stack length and stack position. The results reveal the maximum difference in temperature when stack moves towards the closed side of the resonator tube. A temperature difference of 9 degrees was observed for Aluminum foil when the stack was placed at the optimal position having optimal length. It was very complex to cover at the operating parameter for the investigation of thermoacoustic system. Therefore, further studies should focus on the interdependence between the geometrical parameters and the corresponding frequencies. Further researches within this field will provide more chances to cool an auditorium or a stadium by the energy of sound.

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