Experimental Study of Thermo-Acoustic Refrigeration System: A Review

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Abstract- **In today's world refrigerator has become the need of common society. Basically modern refrigerators operate on VCR system which is quiet efficient but utilizes harmful refrigerants [once chlorofluorocarbons (CFCs), now hydrofluorocarbons (HFCs)] which are ozone depleting chemicals which are major cause of concern. Also it possesses moving parts which reduces its service life & undoubtedly increases its maintenance life. So here we have made an attempt to not only replace the existing refrigeration system but also to make it suitable w.r.t environment affability and provide efficient means of refrigeration which would be not only cost efficient but also maintenance free at its most suitable level.**

Index Terms- **Environmentally friendly, Thermo acoustic Refrigeration, Desired output, Performance Optimization.**

1. INTRODUCTION

From creating comfortable home environments to manufacturing fast and efficient electronic devices, air conditioning and refrigeration remain expensive. However, in an age of impending energy and environmental crises, current cooling technologies continue to generate greenhouse gases with high energy costs. Thermo acoustic refrigeration is an innovative alternative for cooling that is both clean and inexpensive. Refrigeration relies on two major thermodynamic principles. First, a fluid's temperature rises when compressed and falls when expanded. Second, when two substances are placed in direct contact, heat will flow from the hotter substance to the cooler one. While conventional refrigerators use pumps to transfer heat on a macroscopic scale, thermo acoustic refrigerators rely on sound to generate waves of pressure that alternately compress and relax the gas particles within the tube. The model constructed for this project employed inexpensive, easily available materials. Although the model did not achieve the original goal of refrigeration, the experiment suggests that thermo acoustic refrigerators could one day be viable replacements for conventional refrigerators. Thermo acoustics is based on the principle that sound waves are pressure waves. These sound waves propagate through the air via molecular collisions. The molecular collisions cause a disturbance in the air, which in turn creates constructive and destructive interference. The constructive interference makes the molecules compress, and the destructive interference makes the molecules expand. This principle is the basis behind the thermo acoustic refrigerator. One method to control these pressure disturbances is with standing waves. Standing waves are natural phenomena exhibited by any wave, such as light, sound, or water waves. In a closed tube, columns of air demonstrate these patterns as sound waves reflect back on themselves after colliding with the end of the tube. When the incident and reflected waves overlap, they interfere constructively, producing a single waveform. This wave appears to cause the medium to vibrate in isolated sections as the traveling waves are masked by the interference. Therefore, these "standing waves" seem to vibrate in constant position and orientation around stationary nodes. These nodes are located where the two component sound waves interfere to create areas of zero net displacement. The areas of maximum displacement are located halfway between two nodes and are called antinodes. The maximum compression of the air also occurs at the antinodes. Due to this node and anti node properties, standing waves are useful because only a small input of power is needed to create a large amplitude wave.

This large amplitude wave then has enough energy to cause visible thermo acoustic effects. All sound waves oscillate a specific amount of times per second, called the wave's frequency, and is measured in Hertz. For our thermo acoustic refrigerator we had to calculate the optimal resonant frequency in order to get the maximum heat transfer rate. The equation for the frequency of a wave traveling through a closed tube is given by:

$f = a/2L$

Where f is frequency, a is velocity of the wave, and L is the length of the tube

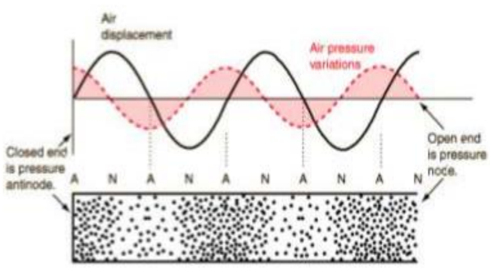

Fig 1: Pressure variation of air

The second fundamental science behind thermo acoustics is thermodynamics, the study of heat transfer. The Ideal Gas Law states that the pressure on a gas is directly proportional to absolute temperature or, as the pressure on a gas increases, the temperature increases. On a microscopic scale, the gas particles in a system will collide more frequently if the temperature is increases or if the volume is reduced. The basic thermodynamic cycles rely on this relationship between temperature and pressure. In any heat cycle, gases will expand and contract, circulating heat throughout the system. These movements of kinetic energy can be used to do work. Depending on how the heat oscillations are controlled, different heat cycles become more efficient, involving less loss of heat from the system. Thermo acoustic refrigerators use variations of these cycles to pump heat.

2. LITERATURE REVIEW

The idea of using sound wave for cooling gained interest in the 1960s. Even though the physical explanation of this refrigeration technique is simple, analysis of the phenomenon and the equations that describe it are not simple. The discovery of the thermo acoustic phenomenon goes back to more than a century ago; however, the significant work in this area was started about two decades ago at the Los Alamos National Laboratory. They have developed different types of thermo acoustic refrigerators and heat engines. A few other research groups are also working in this area. However, the development of such devices is still at preliminary stages. Garret et al. developed a new space craft cryocooler, which uses resonance high-amplitude sound waves in inert gases to pump heat, which was used in the space shuttle discovery. Tijani et al. achieved temperature as low as -65 degree Celsius in their thermo acoustic devices. They used it to study the effect of some important thermo acoustic parameters, such as the prandtl number by using binary gas mixture. Bailliet et al. measured the acoustic power flow in the resonator of a thermo acoustic refrigerator by using Laser Doppler Anemometry (L.D.A) together with microphone acoustic pressure measurement. They found good agreement between the experimental and theoretical results. Jin et al. studied thermo acoustic phenomenon in a pulse tube refrigerator. They studied the characteristics of the thermo acoustic prime mover and the effects of working fluid. They achieved a cryogenic temperature of 120 K in their experiments. Symko et al. used thermo acoustic refrigerator and prime mover to remove heat from an electronic circuit. They drove the thermo acoustic devices at frequencies between 4-24 kHz and investigated the performance of the devices. Jebali et al. analyzed experimentally the performance of a thermo acoustic refrigerator subjected to variable loading and compared the experimental data with the computed data. In their experiments, the hot heat exchanger was maintained at ambient temperature and the temperature of the cold heat exchanger was varied to achieve temperature difference of 0.5 and 10 K along stack. They measured and calculate cooling load for these temperature differences while varying the driving frequency between 30 and 65 Hz. Sakamoto et al. conducted experiments on a thermo acoustic cooler consisting of acoustic loop-tube with two stacks inside. Stack 1 was employed as a prime mover and stack 2 as a heat pump. They used the mixture of air and helium gas at atmospheric pressure as the working fluid. They observed a temperature drop of approximately 289K. They also found that the self sustained sound has higher harmonics which lowered the efficiency of the system. Tijani et al.

described an analytical model of the interaction between a sound wave and a solid surface. They found that the thermal relaxation dissipation at the gas is minimal whenever the temperature oscillations in the wall follow the temperature oscillations in the gas. Huelsz et al. found expressions for the plate difference, between the temperature and pressure waves by using a single plate linear theory for the thermo acoustic phenomenon at ideal conditions. Thermo acoustic refrigerator is a device that operates efficiently by using sound wave, environmentally friendly non flammable gases, and is suitable for handling residential refrigeration need. The thermo acoustic refrigerator has no moving part, and is relatively simple and inexpensive to construct and operate. Thermo acoustic refrigerators tend to be compact and lightweight, and contain no harmful refrigerants, which make them environmentally friendly. This aspect will make it a very appealing option in the future.

Samir Gh. Yahya, Xiaoan Mao and Artur J. Jaworski, In a standing wave thermoacoustic refrigerator, heat transport from the "cold" to the "ambient" end of a stack is achieved by means of an oscillatory motion of a compressible fluid undergoing cyclic compression and expansion. However, the stacks can be both costly and impractical to fabricate due to material and assembly costs, which limits the cost benefits of thermoacoustic systems. Some of these problems could be solved by the application of stacks that have irregular geometries, for instance stacks made of "random" materials from metal machining (swarf), which are often considered as waste. In this paper, the thermal performance of stacks made of a few selected materials is determined by carrying out experiments in a standing wave thermoacoustic refrigerator. The reported results will be beneficial for developing low-cost thermoacoustic refrigerators or heat pumps for both domestic and commercial applications.

In this paper, the experimental method to evaluate the thermal performance of stacks in a standing wave thermoacoustic refrigerator is described. Random stack materials such as stainless steel wool, copper scourers and preformed reticulated vitreous carbon foam were tested. Furthermore, stacks made from Mylar sheets and stainless steel sheets were used as reference test cases. The experimental results reveal that among the tested random stack materials, the steel wool stacks with $rh/\delta k$ of 2.0 and 1.1 achieved the maximum cooling power, the lowest temperature and the highest COPR. Other random material stacks underperform the steel wool stacks, which is partially due to higher values of $rh/\delta k$. This is particularly the case for copper scourers stacks, caused by the difficulty in packing with the current packing method.

For the parallel plate stacks, Mylar sheets stack clearly showed a better performance in comparison to both parallel plate stacks and random material stacks. It achieved a maximum COP, COPR and a temperature difference of 0.217, 0.15% and 7.7 °C, respectively. Further analysis of the hydrodynamic and thermoacoustic characteristics of the tested materials would be beneficial to improve the thermal performance of such a thermoacoustic refrigerator equipped with a stack made of random material, when a low cost device with slightly lower performance found its application.[1]

3 COMPARATIVE STUDY

In this section,69 selected articles dating from 1996 to 2015 engaged in experimental, analytical, and numerical optimization methods were chosen to identify the different research with the methodologies employed for analyzing and optimizing the performance-as defined by there searchers-of the standing wave thermoacoustic refrigerator.

3.1. Stack

Stack is the most important part of a thermoacoustic system. The transfer of heat from a low temperature to a high temperature heat source occurs via this secondary medium, a solid. As the heat is carried from one heat source to another, it is temporarily stored in the stack during the final stage of the compression (pressure antinode) or expansion (pressure node) cycle of the oscillating fluid particles. The heat transfer between the gas and the plate occurs within a thermal penetration depth (thermal boundary layer) where pure conduction takes place. To get the greatest amount of cooling, a large heat transfer area should be used. Therefore, the stack is generally made of many solid walls that are separated by 2δk to 4δk [71].

3.1.1. Stack geometry

Among past stack geometry employed, the commonly used ones are the spiral, parallel, honeycomb and corning celcor types, as shown in Fig. 2. The main objective for the stack geometry selection is to increase the thermal boundary layer surrounding the solid walls where thermoacoustic effects can occur favorably. The desired separation gap between the solid walls has been reported to be between 2 and 4 thermal penetrations depths [21,51,71]. If the walls of the stack are too close, gas parcels cannot pass through the stack efficiently since the viscous properties of the working fluid prevent the working fluid from oscillating. If the walls are too far apart, effective heat transfer between the gas packets and stack walls cannot occur effectively. It would seem that the pin-array stack with its large amount of thermal boundary layers per unit area of solid wall would be ideal [72], as supported by the Rott's function. The ease of fabrication and availability, however, weighs down on the final decision of the selected stack

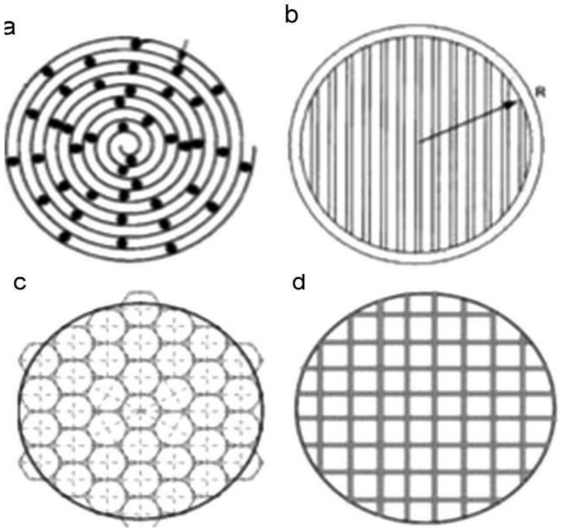

Fig. 2. Different stack geometries utilized in the previous studies (a) spiral [22] (b) parallel plate [73] (c) honeycomb and (d) corning celcor [52].

3.2. Working fluid

The inert gases have been identified as the best working fluid for the thermoacoustic refrigerator [28], and this has been the pulling power of thermoacoustic refrigeration technology, causing no hazardous effects on our environment. Cooling power is pro-portional to sound velocity in gas. Thehigher is the sound velocity, the larger is the cooling power. The sound velocity in gasses such as Helium is high. Furthermore, as the thermal conductivity of the working gas gets higher, the heat transfer between the oscillating fluid particles and the stack walls get easier. These results in the thickening of the thermal penetration depth desired for cooling effects. Other types of heavy inert gases like argon and xenon are usually blended with helium [3,4,5,9,19,34] to increase the effi-ciency of heat transfer within the stack region, as shown in Table 2. A small portion of these types of gas increases the Prandtl number. As a result, the friction between the gas and the solid surface inside the system decreases and the coefficient of performance of the system increases. However, since the sound velocity of these gases is lower than that of pure helium, the resultant sound velocity gets smaller and the cooling power of the system decreases, thus pure form of the heavy gases is not used.

3.3. Resonator

Resonance tube encloses the working fluid, stack, heat exchangers, and an acoustical source to generate acoustical power. The name indicates that the power forced into the tube must be at the natural frequency of the enclosure to generate significant cooling at the solid walls of the stack. The most common reso-nance tubes are the half-wave length and quarter wave length resonators in order to generate a considerable temperature dif-ference between the ends of the short stack positioned in the path of the oscillating working fluid particles. The gas inside a resonator tube can be considered as three different parts; the fluid particles adjacent to the plates that transfer heat, those close to the inside

Table 1

Working fluid mixtures employed in previous studies

Authors	Years	Working fluid
Garret et al. [77]	1993	Helium–Argon Helium–Xenon
Minner et al. [3]	1996	Helium–Xenon
Wetzel and Herman [9]	1996	Helium–Xenon,Helium–Krypton Helium– Argon
Tijani et al. [19]	2002	Helium–Xenon, Helium–Krypton Helium– Argon
Insu et al. [34]	2007	Helium–Xenon

surface of the resonance tube which has dissipative effects, and the rest that are adiabatically compressed and expanded. To reduce the dissipative effects inside the resonance tube, the quarter wavelength tube is used. Some types of resonator tubes are shown in Fig 3.

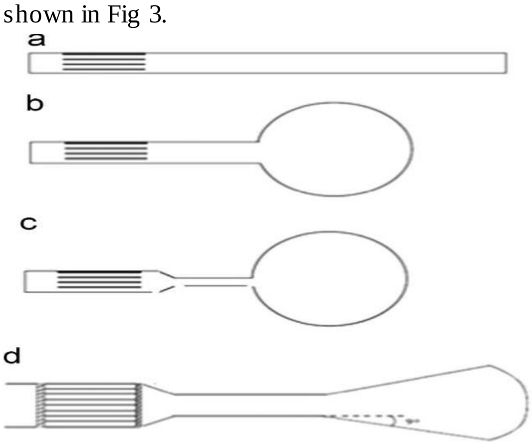

Fig. 3. Types of resonator: (a) half wavelength (b) quarter wavelength with sphere buffer volume (c) two diameter of resonator with sphere buffer volume and (d) two diameter of resonator with conical buffer volume

A half wavelength resonance tube is seen in Fig. 4a [19] while a quarter wavelength length tubes is shown in Fig. 4b [7]. A Hofler resonance tube shown in Fig. 4c [7] has the smallest area by having two tubes, one larger than the other, thus the losses in this system are the lowest. The stack is housed in the larger tube [7]. However, since the buffer volume in the Hofler tube occupies much space, improvement was obtained by using the cone volume shown in Fig. 4d [19], now commonly used in thermoacoustic systems.

3.4. Frequency

The frequency of acoustic standing wave is determined by the type of gas, the length of resonator and the boundary conditions. As the power density in the thermoacoustic devices is a linear function of the acoustic resonance frequency [78], an obvious choice is thus a high resonance frequency. On the other hand, δ_k is inversely proportional to the square root of the frequency which again implies a stack with very small plate spacing. As a com-promise between these two effects and the fact that the driver resonance has to be matched to the resonator resonance for high efficiency of the driver, most researchers have chosen a frequency between 300 Hz and 500 Hz [5,6,19–21,57,61–63]. The designer has to match the mechanical resonance frequency of the speaker to the acoustic resonance frequency of the resonator.

3.5. Average pressure

Since the power density in a thermoacoustic device is propor-tional to the average pressure, pm [78], it is favorable to choose a mean operating pressure as large as possible. This is determined by the mechanical strength of the resonator. On the other hand, the thermal penetration depth, δ_k, is inversely proportional to square root of the operating pressure, so a high pressure results in a small δ_k, which means small stack spacing. This makes the construction difficult. Although a high pressure promises a higher power density, most of the experimental studies used air at atmospheric pressure [14,22,25,35,37,43,44,47,49,51,53,55,56, 58,59,62–64] due to the complexity of the design, fabrication, and tests involved.

4. THE ANALYSIS METHODS

The use of different analysis method to determine the max-imum performance achievable is important in obtaining credible results. The performance is defined by the lowest temperature obtained [5,16,30], the temperature difference generated across the stack [14,25,30,63], the acoustical work required for cooling [66,67,68], or/and the coefficient of performance (COP) [3,4,9,19]. Models such as the stack with a uniform diameter, the stack with two diameters of resonator, and the stack with two diameter-resonator and an attachment of a buffer volume whether conical or sphere shape were among the models used by the researchers. The methods used to date to validate the models are analytical, mathematical, numerical, and experimental methods. Most of the experimental results were validated with the DeltaE software since DeltaE was developed for the specific use in thermoacoustic system analysis by Ward and Swift [17]. The most common experimental results have been in the form of temperature versus time graphs as shown in Fig. 5 [48]. The performance of the thermoacoustic refrigerator is based on the lowest temperature achievable from the system.

6. CONCLUSIONS

The optimization approach adopted have been generally the experimental or/and numerical methods with discrete variations of the parameters of interest to obtain the desired lowest tem-perature, the highest temperature difference generated across the stack, the lowest acoustical work required for cooling, or/and the highest coefficient of performance (COP). Lately, genetic algorithm has been utilized due to its proven capability in other areas. Based on the review, several conclusions have been drawn and sum-marized as follows:

- Stack geometry should generate as much thermal BL as possible. However, manufacturability is often prioritized in the final choice.
- Stack length and stack center position are dependent on each other, one determines the other and they should simultaneously be considered in optimization of both.
- Mylar is still the superior stack material to date.
- Although mixtures of the rare gases produce better efficiency, the heavier gas tends to slow down the velocity and thus their percentage contribution should be monitored.
- Resonator with dwi-diameter and cone buffer volume produces the best performance due to the decrease in surface area compared with a single diameter resonator.
- Frequency and pressure are inter-dependent variables. Frequency and pressure are usually the predetermined variables in design.

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