DESIGN AND FABRICATION OF THERMO ACOUSTIC REFRIGERATION SYSTEM

Sreenesh Valiyandi

Department of Mechanical Engineering ,

College of Engineering Thalassery, Kannur Kerala, (India)

ABSTRACT

A thermo acoustic refrigeration device (TAR) includes an acoustic wave generation device arranged directed to the channel of a hollow tube, and a regenerator provided at a predetermined position in the channel of the tube. A temperature gradient is obtained across the regenerator by an acoustic wave emitted from the acoustic wave generation device. The working fluid used is air. This work examined the performance of thermo acoustic refrigeration, which is the theory of using sound waves to cool the air. The main aim of this work is to design and construct a small thermo acoustic refrigerator from inexpensive and readily available parts and analysed the results. The design includes dimension of stack, selection of acoustic driver, and acoustic resonator. The experiments showed that while thermo acoustic cooling was possible, high efficiency was beyond our reach due to materials restrictions. We obtained the temperature gradient of 3^0 *C for constructing this simple device. However, from these limitations devised several proposals for increasing the performance of thermo acoustic refrigerators. Experiments show the performance can improve by using a better materials such as high heat carrying capacity materials and the working fluids like inert gases.*

Keywords : Acoustic resonator, stack position, thermal penetration depth, Thermo acoustic refrigeration

I. 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

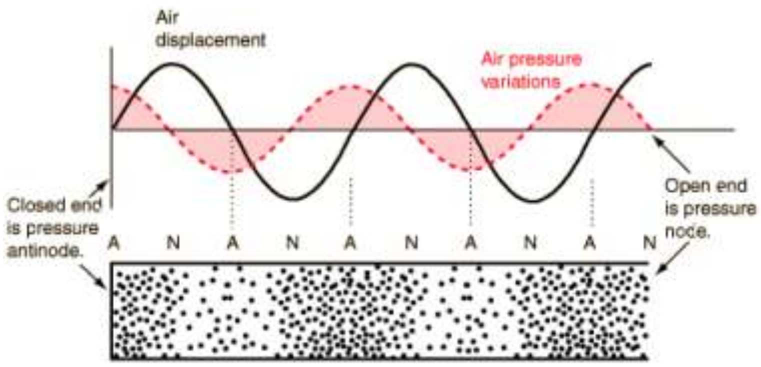

Figure 1.1: Pressure variation of air

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.

II. 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.

III. DESIGN AND FABRICATION OF THERMO ACOUSTIC REFRIGERATION SYSTEM

3. 1 Thermo acoustic Theory

The understanding of acoustic wave dynamics (pressure and velocity field created by an acoustic wave) is necessary to understand the working of a thermo acoustic device. The acoustical theory deals with the study of the longitudinal acoustic waves. The longitudinal acoustic waves are generated as a result of the compression and expansion of the gas medium. The compression of a gas corresponds to the crest of a sine wave, and the expansion corresponds to the troughs of a sine wave. In a longitudinal wave the particle displacement is parallel to the direction of wave propagation i.e. they simply oscillate back and forth about their respective equilibrium position. The compression and expansion of a longitudinal wave result in the variation of pressure along its longitudinal axis of oscillation. A longitudinal wave requires a material medium such as air or water to travel. That is they cannot be generated or transmitted in a vacuum. All sound waves are longitudinal waves and therefore, hold all the properties of the longitudinal waves discussed above. Three properties are necessary for the understanding of the thermo acoustic process. These properties are amplitude, frequency and wavelength.

The displacement of a wave from its equilibrium position is called the wave amplitude. It is also a measure of the wave energy. The time period of a wave is the time required for the complete passage of a wave at a given point. The fundamental wave frequency is the inverse of the time period. In other words, it is the number of waves that pass a given point in a unit time. It is measured in Hertz (Hz), that is, the number of wave that pass in a given point in one second.

The wavelength is defined as the horizontal distance from the beginning of the wave to the end of the wave. It can also be measured as the distance from one wave crest to the next wave crest, or one wave trough to the next wave trough. In acoustics, We can define wavelength as the distance between the two successive compression and expansions.

As mentioned earlier, the compression and expansion of an acoustic wave result in pressure variations along the waveform. This pressure variation is the key process that causes the thermo acoustic phenomenon.

From the ideal gas equation of state,

$$P / \rho = RT$$

Where P is the pressure, ρ is the density, T is the absolute temperature, and R is the gas constant. The above equation indicates that if the density variations are very small, the change in pressure causes the change in temperature. That is an increase in pressure causes an increase in temperature and vice versa.

3.2 Thermodynamic Considerations

In this section, we will discuss the thermo acoustic phenomenon based on acoustics and thermodynamics. To understand the phenomenon, consider a thermo acoustic cooling device such as refrigerator. This device consists of an acoustic driver attached to an acoustic resonator filled with the working fluid, air in this project, inside the resonator tube, a stack of thin parallel plate is installed for the heat transfer.

The acoustic driver connected to one end of he resonator tube excites the air and creates a standing acoustic wave inside the tube. Hence the gas oscillates inside the resonator with compressions and expansions. The length of the resonator tube is set equal to one half of the wavelength of the standing wave i.e. $\lambda/2$.

The standing wave creates velocity nodes at the two ends of the tube and a pressure node at the middle of the tube. If a stack of parallel plates is placed inside the tube, the gas will be at a higher pressure at the end of the stack, which is closer to the end of the tube, than the other end of the stack. This high pressure results in an increase in the temperature of the gas and the excess heat is transferred to the stack, causing an increase in the temperature of the stack at that end and an average longitudinal temperature gradient along the stack is established.

3.3 Design considerations

This work deals with the design and development of the thermo acoustic refrigerator. The linear thermo acoustic theory will be used for the design analysis. Due to the large number of parameters, a choice of some parameters along with a group of dimensionless independent variables will be used.

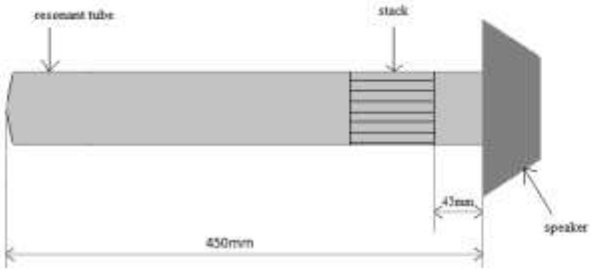

Figure 4.1: Thermoacoustic refrigeration system

3.2.1 Acoustic Driver

The total acoustic power used by the refrigerator is provided by an acoustic driver (speaker). A significant portion of this power is used to pump heat in the stack and the rest is dissipated in different part of the refrigerator. A higher performance of the driver leads to a higher performance of the whole refrigerator system. The acoustic driver converts electric power input to the acoustic power. The most common loudspeaker is of electro dynamic type which uses copper wires and permanent magnet. A Loudspeaker with the maximum power of 1000W at the operating frequency of 385 Hz was selected as the acoustic driver for this project.

3.2.2 Acoustic Resonator

The shape, length, weight and the losses are important parameters for designing the resonator. Length of resonator is determined by the resonance frequency and minimal losses at the wall of the resonator. The length of resonator tube corresponding to half the wave length of the standing wave;

$L = \lambda/2$

And

$\lambda = a/f$

where, a is the speed of sound = 346.5 m/s, λ is the wave length and f is the resonance frequency=385.

λ= 346.5/385 =0.9m =900mm

L_s = 900/2 = 450 mm

As discussed earlier an acoustic driver with the resonance frequency of 385 Hz was selected for the present design. For this resonance frequency the length of the resonant tube was equal to 450mm that corresponds to the half wavelength of the acoustic standing wave, the diameter of the resonator tube was set equal to 70mm to accommodate the size of the acoustic driver.

3.2.3 Stack

The most important components of a thermo acoustic device is the stack inside which the thermo acoustic phenomenon occurs. Thus the characteristics of the stack have a significant impact on the performance of the thermo acoustic device. The stack material should have good heat capacity but low thermal conductivity. The low thermal conductivity for the stack material is necessary to obtain high temperature gradient across the stack and heat capacity larger than the heat capacity of air. In addition the stack material should minimize the effects of viscous dissipation of acoustic power.

There are different geometrical configurations of stack such as; parallel plates, circular, hexagonal and square pin arrays. These geometries are used to have efficient thermal contact between the working fluid and the solid surface across the cross sectional area. The pin array and parallel plates stack have shown to be the best geometries. Numerical studies confirm that efficiency and power are almost 10% to 20% more with parallel sided channel than honeycomb channel. The best location to put stack inside the resonator is about λ/20 from the nearest velocity node. In this project, aluminum foil is used as the stack and is placed 45 mm from the speaker end.

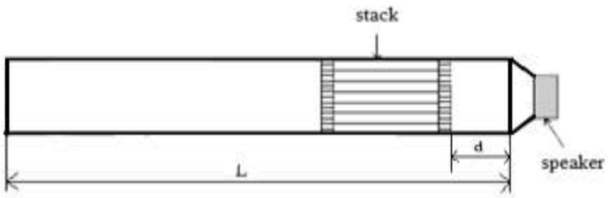

Figure 4.1: Stack position

$d = \lambda/20 = 900/20 = 45mm$

There are three main stack design parameters which are normalized stack position (X_n), normalized stack length (L_n), and the stack cross sectional area (A). Typically, the resonator tube cross sectional area is equal to the stack cross sectional area. The dimensionless parameters, X_n and L_n are defined as,

$X_n = (2\pi f/a)X_s$

$L_n = (2\pi f/a)L_s$

Where, Ls is the length of the stack and Xs is the distance from the mid length of stack to the nearest end of the resonator tube. Some other normalized parameters used in the design of the stack are;

$\Delta T_{mn} = \Delta T_m/T_m$

$\Delta_{kn} = \delta_k/y_0$

Where ΔT_m is temperature difference across the two ends of stack, Tm is the mean air temperature inside the resonator tube, ΔT_{mn} is the normalized temperature difference, δ_k is the thermal penetration depth, and y_0 is the half of the spacing length between the stack layers, and δ_{kn} is the normalized thermal penetration depth.

3.2.4 Working Fluid

Many parameters such as power, efficiency etc. are involved in the selection of the working fluid, and it depends on the application and objective of the device. Thermoacoustic power increases with an increasing the mean pressure inside the resonator. It also increases with an increase in the velocity of sound in the working fluid. The lighter gases such as H2, He, Ne have the higher sound velocity. Lighter gases are necessary for the refrigeration application because heavier gases condense or freeze at low temperatures, or exhibit non ideal behavior. Air at atmospheric pressure is chosen as a working fluid for the present study.

3.2.5 List of Materials

The list of materials used for the fabrication of the thermo acoustic refrigeration system are shown in the table.The resonator is a glass tube of 70 mm diameter. The stack is made of aluminum foil.

Sl. No.	Parts	Qty.	Material
1	The Resonator	1	Glass tube
2	The Stack	1	Aluminum foil
3	Speaker	1	
4	Amplifier	1	
5	Frame	1	Mild steel
6	Electric circuit	1	
7	Temperature Sensor	1	-

Table 3.1: List of materials

3.3 Fabrication of Thermo acoustic refrigeration system

The components of thermo acoustic refrigerators are designed, and the many design parameters are selected in the previous chapter. In this chapter the fabrication of thermo acoustic refrigerator is described.

Figure 3.1: Fabricated model

Based on the design and selection described in chapter 3, some standard components of the thermo acoustic refrigerator were purchased and fabricated. The details of each component are described below.

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3.3.1 Acoustic Driver

A thermo acoustic cooling device requires an acoustic driver attached to one end of the resonator, in order to create an acoustic standing wave in the gas at the fundamental resonant frequency of the resonator the acoustic driver converts the electric power to the acoustic power. In this study a loudspeaker with an operating frequency of 385 Hz was used as the acoustic driver. The loudspeaker was driven by a power amplifier to provide the required power to excite the working fluid inside the resonator.

3.3.2 Acoustic Resonator

The acoustic resonator was built from a straight glass tube of length 450 mm and diameter 70mm.one end of the tube was open to attach the speaker and the other end is closed. In this design the resonant frequency of the resonator is 385 Hz. Thus the length of the tube was set equal to 450mm that corresponds to the half wavelength of the acoustic wave generated at this frequency.

3.3.3 Stack

The stack is inserted in the resonant tube so as to obtain the temperature gradient across the stack. In this project, aluminum foil with parallel plate geometry was used as the stack. The stack is placed in the resonator at a distance of 270mm from the speaker and as described earlier.

IV. RESULT AND DISCUSSION

We analyze the performance of thermo acoustic refrigeration system and we get a temperature difference of 3 degree Celsius between the two ends of the stack.

Ambient Temperature (hot end) T_H=37 degree Celsius	
Time(mm)	T_C (cold end temp.)
15	33
30	32
45	32
60	31
75	31
90	30

Table 4.1: Cold end temperature at one end of the stack

The graph shows temperature at the cold end and the time. From the graph it is seen that the temperature at the cold end decreases with time and reaches a temperature of 30 degree Celsius in 90 minute with a drop in temperature of 3 degree Celsius. The simple experiment of thermo acoustic system shows a temperature gradient of 3^0 C we can develop this system to cool industries. The sound produced by working machines in industries can be used for operating the thermo acoustic refrigeration to cool the rooms.

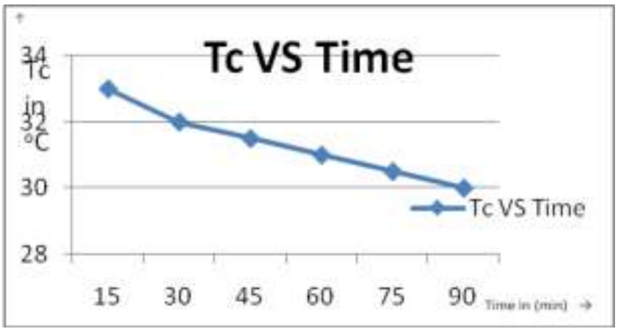
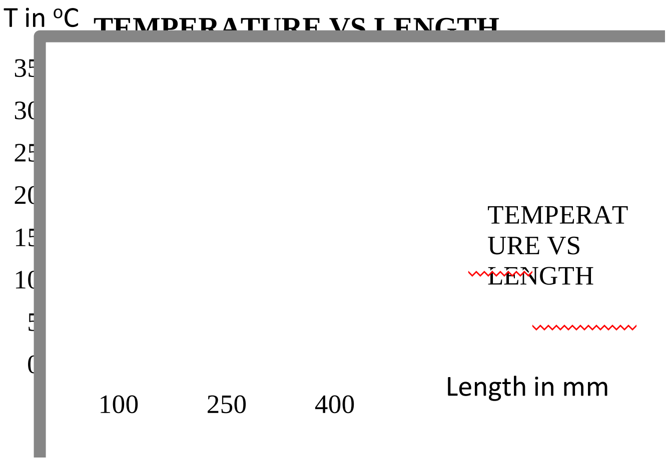


Figure 4.1Temperature Distribution in the Resonator Tube without the Stack

In this set of experiment, the temperature field inside the resonator tube was measured without the stack, in the presence of the acoustic wave. The temperature at 3 points inside the resonator along the length of the resonator was measured by using thermocouples.



V. CONCLUSION

Thermo acoustics is a promising area, which if properly explored, could serve as a good refrigeration system. However, the performance of these device is currently very low. The main motivation for the present work was to develop a simple thermo acoustic refrigerator that is completely functional. This project reports on the design and fabrication of a simple thermoacoustic refrigeration system with inexpensive and readily available material. The characteristic of the fabricated refrigerator and its performance were analyzed experimentally and the results are discussed. The results have shown that without a stack, no temperature gradient is established inside the resonator. Once the stack is placed the temperature gradient is established across the stack. For the given operating condition a temperature gradient of 3 degree Celsius could be established across the stack.

Our device worked as a proof of concept device showing that a thermo acoustic device is possible and is able to cool air, for only a short period of time. If we were able to build the device with better materials, such has a more insulating tube, we might have been able to get better results. In order to create a working refrigerator we probably would have to attach a heat sink to the top of the device, thus, allowing the excess heat to dissipate to the surroundings.

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