# Literature Review on Study of Looped Travelling Wave in Thermo Acoustic Refrigerator

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**Abstract** - Thermo acoustic have been known for over years but the use of this phenomenon to develop engines and pumps is fairly recent. Thermo acoustic refrigeration is one such phenomenon that uses high intensity sound waves in a pressurized gas tube to pump heat from one place to other to produce refrigeration effect. In this type of refrigeration all sorts of conventional refrigerants are eliminated and sound waves take their place. All we need is a loud speaker and an acoustically insulated tube. Also this system completely eliminates the need for lubricants and results in 40% less energy consumption. Thermo acoustic heat engines have the advantage of operating with inert gases and with little or no moving parts, making them highly efficient ideal candidate for environmentally-safe refrigeration with almost zero maintenance cost. Now we will look into a thermo acoustic refrigerator, its principle and functions.

**Keywords - COP, Thermo Acoustic, Refrigerator, Refrigerants, Performance, Efficiency.**

# 1. INTRODUCTION

From creating comfortable home environment to manufacturing fast and efficient electronic devices, air conditioning and refrigeration remain essential services for both homes and industries. It is becoming increasingly important in the design and development of refrigerating systems to consider environmental impacts. To eliminate the use of environmentally hazardous refrigerants, research efforts are focusing more on the development of alternative refrigerants and alternative refrigeration technologies. An approach in the category of alternative technologies is thermo-acoustic refrigeration which produces cooling from sound. The thermo-acoustic effect was first discovered in the 19th century when heat driven acoustic oscillations were observed in open-ended glass tubes. These devices were the first thermo-acoustic engines, consisting of a bulb attached to a long narrow tube. It was in the 1980's that thermo-acoustic refrigerator was first developed, when a research group at the Los Alamos National Laboratory showed that the effect could be used to pump heat. Thermo acoustics is now of large interest in the academic circles of acoustics, thermodynamics and cryogenics and also in the related industries. The technology has seen rapid growth since then, developing it to a promising asset as a clean and environmentally friendly refrigeration method. [2]

# 2. LITERATURE REVIEW

T. Jin, R. Yang, Y. Wang, Y. Feng, K. Tang of china in 2016 analyzed the travelling wave refrigerator and found the expressions for the coefficient of performance and efficiency of the system. They proposed thermo acoustic refrigerator with one engine stage and one refrigerator stage connected with two resonators. The basic aim is to increase the contact between the gas parcels and the thermal walls. [1]

Florian Zink, Jeffrey S. Vipperman, Laura A. Schaefer have done the work in thermo acoustic refrigeration and published a paper named 'Environmental motivation to switch to thermo acoustic refrigeration'. In the paper they described waste heat is the key factor in implementation of this refrigerator. [2]

M. Pierens, J.P. Thermeau, T. Le Pollès and P. Duthilin in paper "Experimental characterization of a thermo acoustic travelling wave Refrigerator" obtained a coefficient of performance relative to Carnot of 30 % with a cold power of 210 W at 233 K. [3]

M.M. Bassem, Y. Ueda, A. Akisawa designed, constructed, and tested A travelling wave thermo acoustic refrigerator. They compared the results of calculated and experimented results. Refrigerator was composed of a linear motor, a branched tube, and a looped tube. The refrigerator reached a minimum cooling temperature of 232 K and 20% of the Carnot COP at 265 K. [4]

# 3. <u>METHODOLOGY</u>

### 3.1 Principle

Thermo acoustics is based on the principle that sound waves are pressure waves. These sound waves propagate through air via molecular collisions. The molecular collision causes 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.

Refrigeration depends 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.

There are two types of thermo acoustic devices namely thermo acoustic engine and thermo acoustic refrigerator. In a thermo acoustic engine, heat is converted into sound energy and this energy is available for the useful work. In a thermo acoustic refrigerator the reverse process occurs, i.e. it utilizes work in the form of acoustic power to absorb heat from a low temperature medium and reject it to a high temperature medium .[5]

### 3.2 Basic Considerations
### 3.2.1 Thermodynamic Consideration

A thermo acoustic device consists of an acoustic driver attached to an acoustic resonator tube filled with the working fluid. Inside the resonator tube, a stack of thin parallel plates and two heat exchangers (hot and cold) are installed for the heat transfer. The schematic of a typical thermo acoustic device is shown in the below figure.
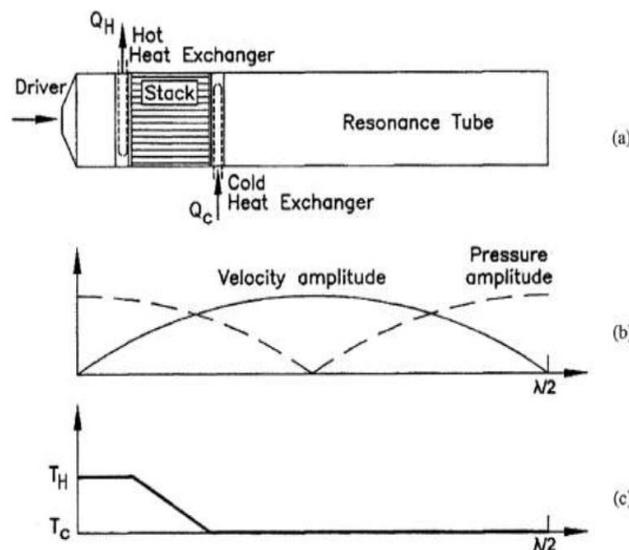


**Figure 3.1, (a) Schematic of a thermo acoustic refrigerator. (b) Velocity and pressure variation across the resonance tube. (c) Temperature variation across the resonance tube [5].**

The acoustic driver, connected to one end of the resonator tube, excites the working fluid and creates a standing wave inside the tube. Hence the gas oscillates inside the resonator with expansions and compressions. The length of the resonator tube is typically set equal to one-half of the wavelength of the standing wave, i.e. half of wavelength. The standing wave creates velocity nodes at the two ends of the tube and a pressure node at the middle of the tube as in the fig. 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 (i.e. left side of the stack in fig), 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.

### 3.2.2 Acoustic Theory

The understanding of acoustic wave dynamics, i.e. the pressure and velocity fields 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 crust of a sine wave, and the expansion corresponds to the trough of a sine wave. An example of how these two relate to each other is shown in the above figure. 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 and/or transmitted in a vacuum. All sound (acoustic) waves are longitudinal waves and therefore, hold all the properties of the longitudinal waves discussed above. Three characteristics of the acoustic waves 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 amplitude. It is also a measure of the wave energy. Larger the amplitude, higher will be the wave energy. Thus, the energy of an acoustic wave can be estimated by measuring its amplitude. The energy or intensity of an acoustic wave is measured in terms of decibel. If the given acoustic wave is comprised of the superposition of different sine waves, then the amplitude and hence the energy of the given wave can be estimated by integrating the energy in all the frequency components of the given wave.
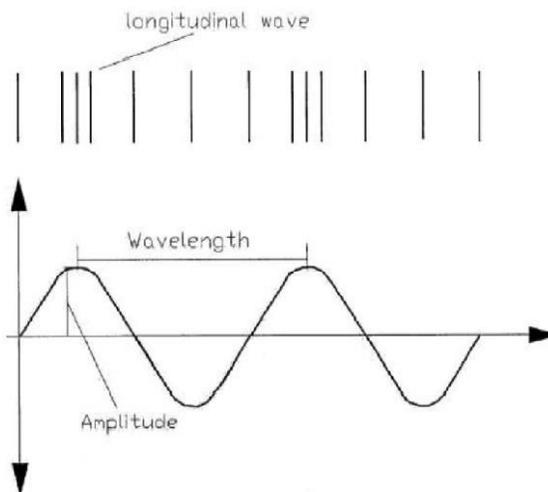


**Figure 3.2, Comparison of a Longitudinal Acoustic Wave with a Sine Wave. [5]**

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), i.e. the number of waves that pass 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 crust, or one wave trough to the next wave trough. In acoustics, we can define wavelength as the distance between the two successive compressions or expansions. 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. These pressure variations can also be used to estimate the sound intensity.

From the ideal gas equation of state,

$$P/\rho = RT$$

Where,

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

### 3.2.3    Working Gas

To achieve high efficiency inert gases like Helium, Xenon, etc. are preferred. They possess low kinematic viscosity as compared to other gases which makes it possible for molecules to vibrate freely even in a small portion resulting in high utilization of gas molecules to participate in heat transfer. It has the characteristics like high velocity of sound and high mean pressure required to generate high acoustic power. Inert gases have certain issues like leakages; cost, refilling, etc. therefore air with high pressure can also be used as a working medium. [3]

**Different Waves**
- *Travelling Waves*

As a wave is observed traveling through a medium, a crest is seen moving along from particle to particle. This crest is followed by a trough that is in turn followed by the next crest. In fact, one would observe a distinct wave pattern (in the form of a sine wave) travelling through the medium. This sine wave pattern continues to move in uninterrupted fashion until it encounters another wave along the medium or until it encounters a boundary with another medium. This type of wave pattern that is seen traveling through a medium is sometimes referred to as a **travelling wave.**

- *Standing Wave*

It is however possible to have a wave confined to a given space in a medium and still produces a regular wave pattern that is readily discernible amidst the motion of the medium. For instance, if an elastic rope is held end-to-end and vibrated at just the right frequency, a wave pattern would be produced that assumes the shape of a sine wave and is seen to change over time. The wave pattern is only produced when one end of the rope is vibrated at just the right frequency. Because the observed wave pattern is characterized by points that appear to be standing still, the pattern is often called a standing wave pattern.

### 3.3    Working

Starting from point 1, the packet of gas is compressed and moves to the left. As the packet is compressed, the sound wave does work on the packet of gas, providing the power for the refrigerator. When the gas packet is at maximum compression, the gas ejects the heat back into the stack since the temperature of the gas is now higher than the temperature of the stack. This phase is the refrigeration part of the cycle, moving the heat farther from the bottom of the tube.

In the second phase of the cycle, the gas is returned to the initial state. As the gas packet moves back towards the right, the sound wave expands the gas. This process results in a net transfer of heat to the left side of the stack. Finally, in step 4, the packets of gas reabsorb heat from the cold reservoir to repeat the heat transfer process [5].
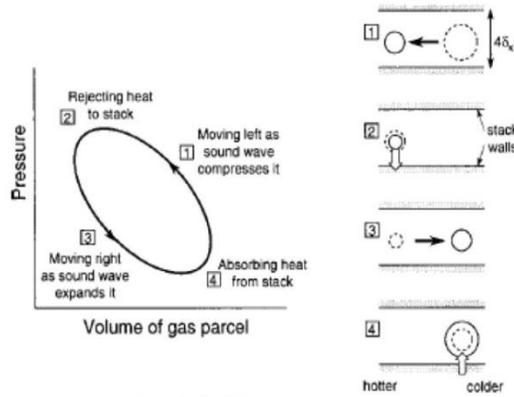
**Fig no. 3.5: P-V Diagram [5]**

# 4. EXPERIMENTATION

**4.1 Design Choices**

The traveling wave thermo acoustic refrigerator that we have designed and constructed consists of a linear motor, a branched tube, and a looped tube having a regenerator as shown in Fig. 6.1(a). The characteristics of parts are as follows: As an acoustic driver, a linear motor (model RM088-042, made by SINFONIA Technology Co., Ltd.) is used. The linear motor is located in a case and connected to the branched resonator via welding bellows.
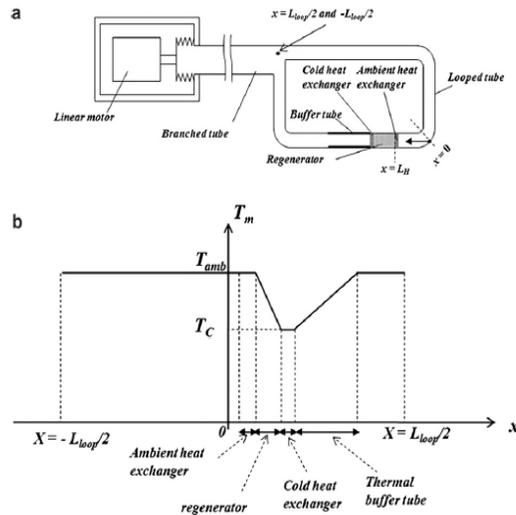


**Fig no. 4.1: (a) Schematic illustration of experimental device (b) Temperature distribution near cold heat exchanger [4]**

The maximum peak-to-peak displacement of the motor is 8 mm. This linear motor is designed to operate at a frequency of about 50 Hz and hence, the driving frequency of the refrigerator is set at about 50 Hz. In order to make the resonance frequency equal to the driving frequency and to excite the half wavelength mode in the device, the total length of the refrigerator is set to 3.5 m. Nitrogen at 0.5 MPa is used as the working gas because the sound speed in it is relatively low comparing with other gases, the looped tube length L loop is fixed to 1.5 m. The branched and looped tubes, which are made from stainless steel, have circular cross sections with inner diameters of 57.2 mm and 40.5 mm, respectively. The diameter of the branched tube is chosen to be larger in order to reduce internal viscous dissipation. A 50 mm long regenerator, composed of stainless steel meshes, is placed inside the looped tube. As described above, the position and the radius of the regenerator has been numerically optimized and

will be presented in the next section because they significantly affect the performance of the refrigerator. However, the regenerator length has not been optimized since it has a small effect on the refrigerator performance. Two heat exchangers are required to supply and remove heat to and from both sides of the regenerator. A cold heat exchanger is placed at the cold side of the regenerator. An electrical heater is bound around it in order to supply heating power, which is regarded as cooling power. The other heat exchanger is placed at the ambient side of the regenerator and its temperature is kept at ambient one. Both heat exchangers, made from brass, consist of parallel plates 0.5 mm thick and spaced 1 mm apart. The porosity of the heat exchangers is 0.67. The lengths of the cold and ambient heat exchangers are 5 and 8mm, respectively.

**4.2 Set Up**

A refrigerator with numerically optimized values of regenerator radius and position was constructed. The optimized regenerator was made of 150-mesh stainless-steel screens (i.e.150 wires per inch). Its effective radius was calculated to be 0.049 mm. This value of radius is the closest to the numerically optimized value presented in the paragraph (0.045 mm). The porosity of the regenerator was also evaluated by measuring its weight; it was found to be0.70. The normalized position of the regenerator loop used in these experiments was 0.07. The difference between this value and the numerically optimized value given in the previous paragraph (0.1) corresponding to a distance of 40 mm does not affect significantly the COP as can be seen in Fig. The main dimensions and characteristics of the constructed refrigerator are listed in Table 4.1. Measurements of both cooling power and input acoustic power are required to determine the COP of the refrigerator. Electric power supplied to the heater wound around the cold heat exchanger was used as cooling power. The input acoustic power is determined as follows: pressure amplitude and phase were measured at two positions on the branched tube and the acoustic power at the end of the branched tube was then calculated using the linear acoustic theory, which includes thermal and viscous effects. We have set this acoustic power as the input acoustic power. Two thermocouples mounted on the external surface of the cold and ambient heat exchangers are used to measure their temperatures. By a chiller, the temperature of the ambient heat exchanger is kept between 24ºC and 26ºC. To reduce thermal losses, the regenerator and thermal buffer tube were insulated using glass wool. To minimize the effect of streaming a membrane made from elastic material was introduced inside the looped tube near the ambient heat exchanger. Various values of standard refrigerator system is elaborated below in the given table.

| Characteristics of the refrigerator | |
| --- | --- |
| Frequency (Hz) | 50 |
| Mean Pressure (MPa) | 0.5 |
| Looped Tube Length (m) | 1.5 |
| Looped tube diameter (mm) | 40.5 |
| Branched tube length (m) | 2 |
| Branched tube diameter (mm) | 57.2 |
| Regenerator length (mm) | 50 |
| Regenerator radius R (mm) | 0.049 |
| Regenerator porosity | 0.7 |

| | |
|---|---|
| Regenerator normalized position | 0.07 |
| Cold heat exchanger length (mm) | 5 |
| Cold heat exchanger porosity | 0.67 |
| Ambient heat exchanger length (mm) | 8 |
| Ambient heat exchanger porosity | 0.67 |

**Table no. 4.1: Characteristics of the refrigerator**

**4.3 Results**

Open circles in Fig. 4.2 represent the experimental results of the input acoustic power as a function of $T_C$.
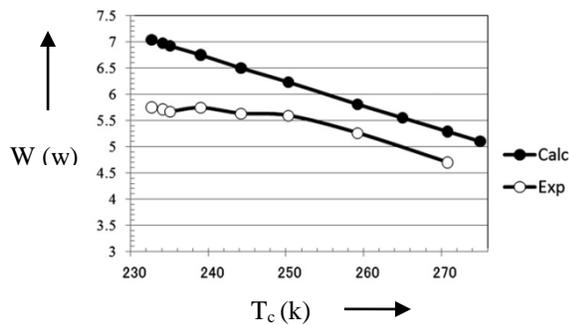


**Figure 4.2: Input acoustic power as a function of cold heat exchanger temperature [4]**

When $T_C$ reaches about its minimum value (232 K) the measured input acoustic power equals 5.8 W. This value decreases when $T_C$ increases to reach 4.7 W at $T_C$ = 270 K, while pressure amplitude at the junction position was kept at 22kPa. This indicates that the acoustic field inside the refrigerator depends on the temperature of the cold heat exchanger.
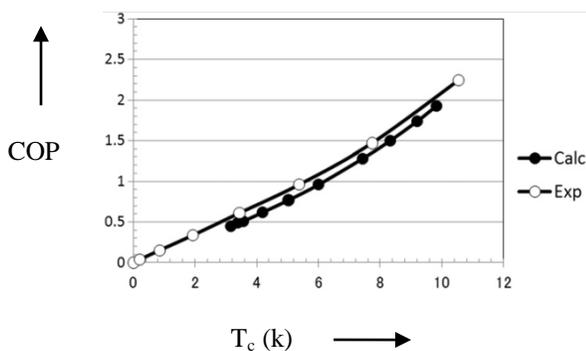


**Fig no. 4.3: COP as a function of cooling power [4]**

Fig. 4.3 shows the experimental results of the COP as a function of cooling power represented by open circles. The value of COP reaches 2.4 when cooling power becomes 11 W, corresponding to a cooling temperature of 270 K. This increase in the COP at high cooling power due to the increase in $Q_C$ and decrease in W with increasing $T_C$, as shown in Fig, is explained by the decrease of input acoustic power; with increasing $T_C$, $Q_C$ increases but W decreases as shown in figure.
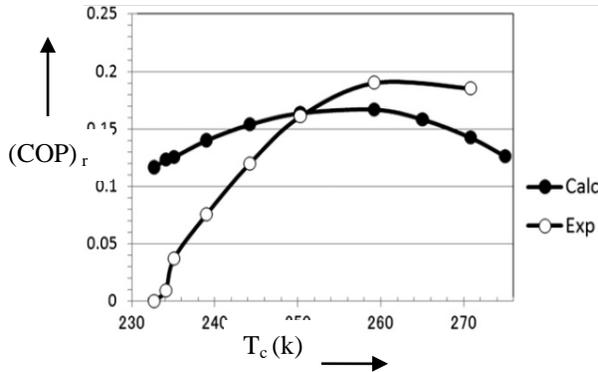


**Fig no. 4.4: (COP)$_r$ as a function of cold heat exchanger temperature [4]**

Open circles in Fig4.4 show the experimental relative COP. (COP)$_r$ as a function of the cold heat exchanger temperature $T_C$. (COP)$_r$ is the ratio of COP and Carnot COP. Carnot COP is defined as:

$$COP_{Carnot} = \frac{T_C}{T_H - T_C}$$

At a cooling temperature of 265 K, the measured relative COP research maximum value of about 20%.

# 5. <u>MERITS AND DEMERITS OF THE TECHNOLOGY</u>

**MERITS OF THE TECHNOLOGY**

Although the working principle of thermo acoustic technology is quite complex, the practical implementation is relatively simple. This offers great advantages with respect to the economic feasibility of this technology. Other advantages are:

1. No moving parts for the process, so very reliable and a long life span.
2. Environmentally friendly working medium (air, noble gas)
3. The use of air or noble gas as working medium offers a large window of applications because there are no phase transitions.
4. Use of simple materials with no special requirements, which are commercially available in large quantities and therefore relatively cheap.
5. On the same technology base a large variety of applications can be covered.

**DEMERITS OF TECHNOLOGY**

1. Efficiency : Thermo acoustic refrigeration is currently less efficient than the traditional refrigerators
2. The coefficient of performance of most advanced TAR is only 1 when compared to 3-4 of modern refrigeration's.
3. Another major problem of TAR is that it is either fully on or Off
4. Lack of interest and funding from industry due to their concentration on developing alternatives gases of CFCs
5. It leaked an incredible amount of sound that causes ear pain but produces only small temperature gradient.

# 6. <u>APPLICATIONS</u>

- ➢ Speaking of its practical applicability, prototype of thermo acoustic refrigerators have operated on the Space Shuttle and abroad a Navy warship.
- ➢ Chip cooling: In this case a piezoelectric element generates the sound wave. A thermo acoustic heat pump cools the chip.
- ➢ Electronic equipment cooling on naval ships: In this application, a speaker generates sound waves. Again a thermo acoustic pump is used to provide the cooling.
- ➢ Though it probably won't be useful for car air conditioning systems any time soon since they are too bulky and heavy, it may prove useful for "niche applications", such as cooling satellite sensors or super fast computers. In addition to being useful on shipboard, this technology could be adapted for soft drink machines, medicine storage, computer chips and food transport companies.
- ➢ Chilled water from the refrigerator circulated through racks of radar electronics on the USS Deyo, a Navy destroyer. Although we can improve the performance substantially with some modest changes, thermo acoustic refrigerators of this type will always have an intrinsic limit to their efficiency.

# 6. <u>CONCLUSION</u>

1. This technology is successfully implemented in Electronic equipment cooling on naval ships**,** where a speaker generates sound waves and again a thermo acoustic pump is used to provide the cooling.

2. This is trending technology now a day as it is being used in gas turbine tri-generation systems, where waste heat is utilized to produce sound waves, which are further used for refrigeration.

3. Acoustic power needs high intensity sound waves for its operation; since it is not available in daily functioning hence its use is limited.

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