IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X
PP. 58-63
www.iosrjournals.org

Thermo Acoustic Refrigeration

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Abstract ; *Thermoacoustic refrigeration is an emerging refrigeration technology which does not require any moving parts or harmful refrigerants in its operation. This technology uses acoustic waves to pump heat across a temperature gradient. The vast majority of thermoacoustic refrigerators to date have used electromagnetic loudspeakers to generate the acoustic input. In this thesis, the design, construction, operation, and modeling of a thermoacoustic refrigerator are detailed. The developed theoretical and experimental tools can serve as invaluable means for the design and testing of other piezoelectrically-driven thermoacoustic refrigerator configurations.*

Key Words — *Thermo-Acoustics, Piezo-Electric effect, Drivers, Working Fluid, Thermal Acoustic Effect.*

I. Introduction

Thermo acoustic refrigerator is a special kind of device that uses energy of sound waves or acoustic energy to pump heat from low temperature reservoir to a high temperature reservoir. The source of acoustic energy is called the „driver which can be a loudspeaker. The driver emits sound waves in a long hollow tube filled with gas at high pressure. This long hollow tube is called as „resonance tube‟ or simply resonator. The frequency of the driver and the length of the resonator are chosen so as to get a standing sound wave in the resonator. A solid porous material like a stack of parallel plates is kept in the path of sound waves in the resonator. Due to thermo acoustic effect (which will be explained in detail in the animation), heat starts to flow from one end of stack to the other. One end starts to heat up while other starts to cool down. By controlling temperature of hot side of stack (by removing heat by means of a heat exchanger), the cold end of stack can be made to cool down to lower and lower temperatures. A refrigeration load can then be applied at the cold end by means of a heat exchanger.

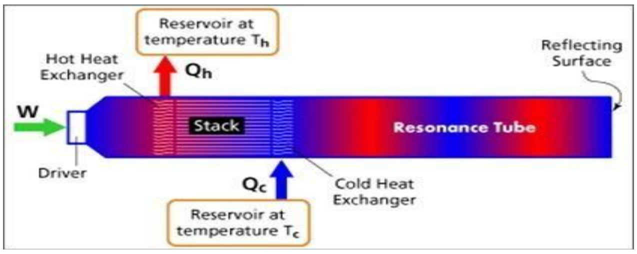

Figure 1.1: Temperature variation in device

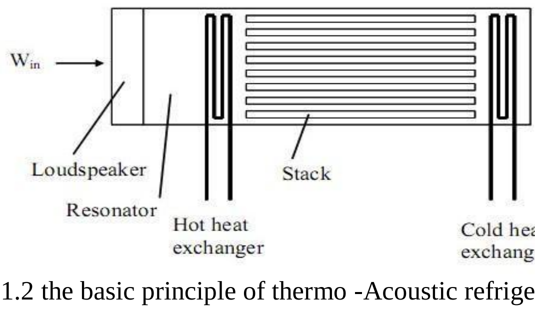

Figure 1.2 the basic principle of thermo -Acoustic refrigeration system

Thermo acoustics combines the branches of acoustics and thermodynamics together to move heat by using sound. While acoustics is primarily concerned with the macroscopic effects of sound transfer like coupled pressure and motion oscillations, thermo acoustics focuses on the microscopic temperature oscillations that accompany these pressure changes. Thermo acoustics takes advantage of these pressure oscillations to move heat on a macroscopic level. This results in a large temperature difference between the hot and cold sides of the device and causes refrigeration.

II. Methods And Procedures

2.1 Thermoacoustic Refrigerator Design

The design of thermoacoustic refrigerators is a field where a lot of research is currently being carried out. This literature contains many ongoing debates as to what the best design techniques may be. This chapter starts off with a basic design strategy for thermoacoustic refrigerators, and then goes on to discuss the individual components in detail, reviewing the relevant literature on the topic.

2.2 Design Overview

Thermoacoustic refrigerators can generally be broken up into four parts.
These parts are known as the driver, the resonator, the stack, and the heat exchangers and are labeled for an example refrigerator in Figure 2.1:

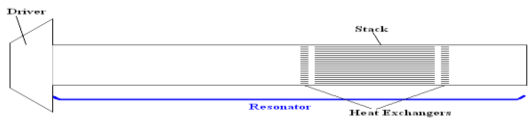

Figure 2.1: A Typical thermoacoustic refrigerator

2.3 Working Fluid

Another important design consideration is the choice of the working fluid which fills the resonator. Both the viscous and thermal penetration depths as well as the natural frequency of the resonator are dependent on the choice of working fluid. Belcer *et al.* points out that a high ratio of specific heat and small Prandtl number are desirable characteristics of the working fluid. The Prandtl number is of particular interest because it is equal to the square of the ratio of the viscous penetration depth to the thermal penetration depth. A small Prandtl number means that the viscous effects are small compared to the thermal effects.

Belcer *et al.*explore this concept further. He suggested that when mixing two binary gases, the minimum Prandtl number occurs when the lighter gas is approximately 66% by volume. He tests his theory and gets reasonable results. However, he concludes that the design applications must be taken into account before selecting a fluid for thermoacoustic devices, citing the example that when small temperature differences are the design goal, mixtures including polyatomic gases with small specific heat ratios may be desired.

Tijani *et al.* Conducted numerous experiments with different gas mixtures used as the working fluid in thermoacoustic refrigerators. Their experiments centered around mixing helium with other noble gases (*Xe, Kr, Ar, Ne*) and studying the effect of the resulting Prandtl numbers on refrigerator performance. They found that though the Prandtl number decreases as the mole fraction of helium to the other noble gas is decreased, the density of the overall working fluid increased. This increase in
working fluid density reduces the cooling power of the system. Because of this tradeoff between efficiency and cooling power comes into play, the authors conclude that the optimal working fluid for helium-noble gas mixtures depends on the design goals of a specific refrigerator.
Giacobbe introduced methods for calculating the Prandtl number, viscosity, and thermal conductance of mixtures of gases. His paper describes experiments using mixtures of helium and other noble gases to validate his theoretical work. His results are in good agreement with his theory which allows this method to be used to obtain good estimations of the Prandtl number for gas mixtures to be made. 100g of weighed plastic granules are fed into the modified pressure cooker. The pressure cooker is modified by attaching a pressure gauge to maintain pressure and a thermocouple is attached to measure temperature. Heat is provided by using Nichrome coil heater which may be between 150-200^{0}C. It is the temperature at which plastic begins to melt and vaporize.
These vapors are passed through copper tubes which are connected to shell and tube heat exchanger. At the end of the heat exchanger, the distillate is collected. The amount of distillate obtained is measured.

2.4 Refrigerator Design

The starting point for the design of this thermoacoustic refrigerator was the driver as it was required . Once a suitable driver was selected, the choice of the resonator and stack followed as detailed in the following sections. This refrigerator was designed to be low cost and easy to assemble and study so that it can be modeled. Once models are created and validated, more expensive and difficult to construct piezoelectrically-driven thermoacoustic refrigerators will then be able to be modeled before massive amounts of effort are put in to construct them.

2.5 Driver Selection

Most piezoelectric drivers consist of a metallic diaphragm with piezoelectric material deposited on it. Electrodes are then attached to the two sides of the piezoelectric material. When voltage is applied across the electrodes, the piezoelectric material expands or contracts while the metal diaphragm is not affected by the voltage. The mismatch in expansion and contraction between these two materials which are bonded together causes a bending moment in the diaphragm. If an AC signal is applied, the diaphragm oscillates back and forth at the frequency of the signal, causing the air around it to oscillate as well.

Figure 2.2 speakers that act as drivers

2.6 Stack Design

Most thermoacoustic refrigerator stack designs are driven by cooling power requirements. For this design however, easily measurable cooling was the only requirement. Therefore, the stack and resonator designs were based off of the design given by Russel and Weibull.

The stack needed spacing on the order of 2 to 4 thermal penetration depths. The calculation of the thermal penetration depth is given in equation (2.16) above and is repeated below after substituting in frequency instead of angular frequency.

The variables that make up the thermal penetration depth are functions of the gas properties and the frequency. Air at room temperature was selected as the working fluid for this refrigerator. The properties for air at room temperature to be used are :

Thermal conductivity k=0.0257 W/m.K *Density p=1.205Kg/m* *Specific Heat Capacity Cp*=1005 J/*kg K*

These variables are then used with equation where f is the driving frequency of the refrigerator. This yields the following: $\delta = 1.3\times10\text{-}4$

Recalling that the stack spacing should be around 2.5 thermal penetration depths, the targeted stack spacing is 0.325mm. A coil design for the stack was then selected for ease of manufacturing. The cross section of the stack was then required to be round. The stack cross sectional area selected to be much smaller than the speaker diaphragm was chosen in order to increase both pressure and volumetric flow rates in the resonator. The final selection was 0.875 (2.14 *cm)* diameter was used because the plastic tubes used for the resonator come in that standard size. The stack length was selected to be 35 mm following Russel and Weibull

2.7 Resonator Design

The resonator design was driven by the need to have a natural frequency near to 400 Hz so as to line up with the speaker natural frequency. It also needed to interface with the speaker and stack cross sections. Finally, it had to be easy to manufacture. A simple tube was selected to be used as the resonator geometry.

This tube made manufacturing very simple. It also made for easy calculation of the resonator natural frequency. At the driver end, the resonator was expanded to meet the speaker as shown in Figure 4.2. The other end was plugged with an aluminum cap as this is the hot end of the refrigerator and the aluminum would help heat to leave the system.

The end of the resonator with the aluminum plug is a pressure anti-node and velocity node. The end near the speaker has close to (but not exactly) the opposite boundary conditions (pressure node and velocity anti-node). The approximate resonator length is calculated as follows:

l=vel⁄4f =343⁄4.40=21.4cm

The resonator length was varied somewhat after experiments were performed and the final resonator length was 9.45” (24 *cm*) which brought the natural frequency to 395 Hz. This variance in length is a result of the resonator boundary conditions at the speaker end being approximate. The resonator cross section had to be round due to the stack. For ease of manufacturing, a 1” (2.54 *cm*) outer diameter, 0.875” (2.14 *cm*) inner diameter tube was to be used. The placement of the top of the stack was selected to be 1.85” (4.70*cm*) from the speaker end of the resonator so that it would be well placed between the velocity and pressure nodes. The aluminum plug was simply selected to seal the end of the tube tightly.

2.8 Construction

The stack and resonator were made in house out of cheap, every day materials as detailed in the following sections. The driver was purchased as it is available commercially. A mount was built to hold the driver in place and is shown in the section on assembly.

Stack Construction

The stack spiral was made using 35 *mm* camera film. To enforce the spacing between the layers, nylon fishing line with a diameter of 0.35 *mm* was glued across the film as shown in Figure 4.3. After the glue dried, the film was rolled up as seen in Figure 4.3, and glued at the very end. The diameter of the rolled up stack is 0.875” (2.22 cm) and its height is 1.38 in (3.5 cm). The strip of film before being rolled up is approximately 20 in (50.8 cm).

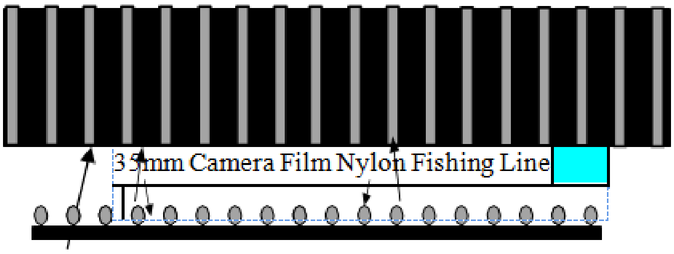

Figure 2.3: Top and side views of the stack before it is rolled up

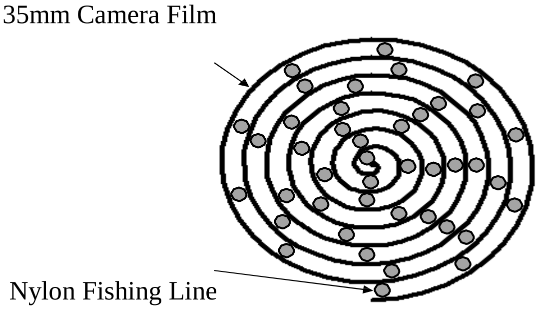

Figure 2.4: Cross sectional view of the stack after it

2.9 Resonator Construction

The resonator was constructed from acrylic tubing with a 1” (2.54 *cm*) outer diameter and 0.875” (2.22 *cm*) inner diameter. An aluminum cap was machined to fit into the end of the tube. An acrylic base plate was used to create an interface between the speaker and the resonator, which was fastened to the resonator tube using an adhesive. Holes were drilled in the base plate which matched the speaker mounting holes for easy attachment to the speaker. The resonator is pictured in Figure 2.2.

2.9.1 Assembly

The stack was positioned inside the resonator tube by sliding it in from the top. The stack was pushed down until its top was 1.85” (4.70 *cm*) from the top of the resonator. Two small holes were then drilled in the side of the resonator so that thermocouples could be used to measure the internal temperature, one hole above the stack and one hole below it. Thermocouples were placed just through the holes and glue was used to both hold them in place and to reseal the holes. The aluminum cap was then placed at the top of the resonator.

The speaker was placed in the mount which had been made for it. The resonator was then placed above the speaker and screws were used to fasten the whole thing together. Figures 2.7 show the assembled refrigerator. The dimensions of the refrigerator are displayed in Figure 2.5.

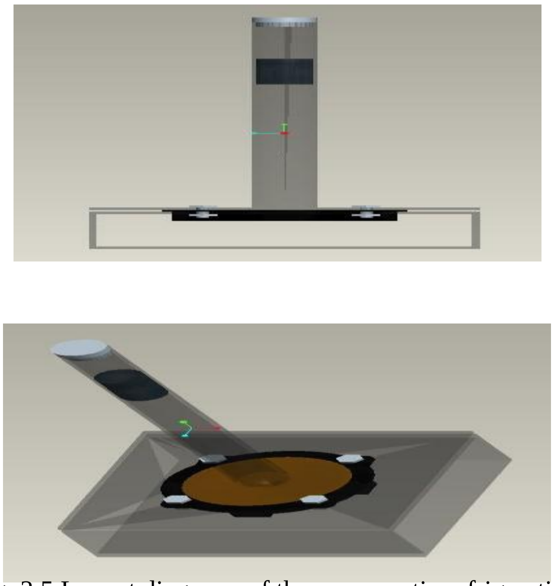

Fig: 2.5 Layout diagrams of thermoacoustic refrigeration

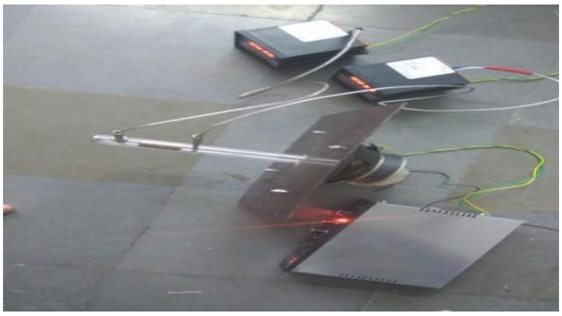

Figure 2.6: Assembled refrigerator

2.9.2 List of Materials

The list of materials used for the fabrication of the thermo acoustic refrigeration system is shown in the table.

Sl.No.	Parts	Qty.	Material
1	The Resonator	1	Glass tube
2	The Stack	1	Aluminum foil
3	Speaker	1	
4	Amplifier	1	
5	Thermocouples	2	-

Table 2.1: List of materials

III. Results And Discussions

In this case, the refrigerator was at its resonant frequency of 80 Hz and a current of 12 V and 200 mA respectively, *i.e.* input power is 7.6 watts. The thermocouple a data obtained at various times throughout the operation of the refrigerator are shown in Figures . It should be kept in mind that the thermocouples are measuring the internal temperatures just above and just below the stack.

The graphs are obtained at the beginning and throughout the experiment. The temperature variation at the stack is plotted.

S. no	Time t in Min	Thermocouple Readings in ^{0}c	
		At Hot End	At Cold End
1	0	30.75	30.75
2	10	33.75	30
3	15	36	29.75
4	25	39	29
5	30	41.75	28
6	35	44.75	26.75

Table 3.1 – Readings of Thermocouple at different time Periods

IV. Conclusion

From the values, we conclude that:

- There was four degrees drop in temperature at the cold chamber.
- For every three degrees rise in temperature at hot end there was one degree drop at cold end.
- The drop in temperature increases with increase in time.

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