Design and Experimental Study of Small-Scale Fabricated Thermo-Acoustic Refrigerator

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***Abstract*— All refrigerator and air conditioning, contains refrigerants that are harmful to environment, CFC's the original refrigerant, are depleting the ozone layer and replaced by HCFC's or HFC's the new product do not appear to harm ozone layer, but they do have the potential to lead to between 100 to 5000 times more global warming than CO_2. The answer to current global warming effect due to conventional refrigeration is Thermo acoustic Refrigeration. Thermoacoustics is a field that combines thermodynamics, fluid dynamics and acoustics. In Thermo acoustics it is possible to construct thermo acoustic refrigerators, thermodynamic engines, prime movers and heat pumps which respectively use heat to create work, and use work to create or move heat. Thermo acoustic refrigerators 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.**

The goal of this investigation was to develop a standing-wave thermo acoustic refrigerator. The refrigerator should have a COP of at least 5. The performances of the thermo accoustic refrigerator with different aspects are discussed as well.

***Keywords*—Thermo acoustics, Sound wave, Stack, Insulation.**

I. INTRODUCTION

The Recent developments in the field of Thermoacoustics promise to revolutionize the way that many machines currently operate. By manipulating the temperature-changes along the acoustic longitudinal waves, a machine can be created that can replace current refrigeration and air conditioning devices. These machines can be integrated into refrigerators, home generators, hot water heaters and coolers [1]. The Thermo acoustics devices contain no adverse chemicals or environmentally unsafe elements that are characteristics of the current refrigeration systems. Thermoacoustics deals with the conversion of heat energy to sound energy and vice versa. There are two types of thermo acoustic devices: Thermo acoustic engine and Thermo acoustic refrigerators. In a thermo acoustic engine, heat is converted into sound energy and this energy is available for the useful work. In this device, heat flows from a source at higher temperature to a sink at lower temperature. In a thermo acoustic refrigerator, the reverse of the above 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 [2].

The Thermo Acoustic phenomenon can be explained as, Acoustic waves experience displacement oscillations, and temperature oscillations in association with the pressure variations. In order to produce thermo acoustic effect, these oscillations in a gas should occur close to a solid surface, so that heat can be transferred to or from the surface. A stack of closely spaced parallel plates is placed inside the thermo acoustic device in order to provide such a solid surface. The thermo acoustic phenomenon occurs by the interaction of the gas particles and the stack plate. When large temperature gradients are created across the stack, sound waves are generated i.e. work is produced in the form of acoustic power (forming a thermo acoustic engine). In the reverse case, the acoustic work is used in order to create temperature gradients across the stack, which is used to transfer heat from a lower temperature medium to a high temperature medium (as the case of a thermo acoustic refrigerator) [3]. A thermo acoustic refrigerator consists of a tube filled with a gas. This tube is closed at one end and an oscillating device is placed at the other end to create an acoustic standing wave inside the tube.

The goal of the investigation is designing, fabricating and analyzing a simple and fundamental prototype thermo acoustic refrigerator and tests it to study the performance.

II. DESIGN CONSIDERATIONS

A thermo acoustic refrigerator basically consists of an acoustic power source, a resonator, a stack and a pair of heat exchangers [4].

A. Working Gas

To get more thermo acoustic power a high mean pressure, a high velocity of sound and a large cross-sectional area are required. For this reason, helium is commonly used in thermo acoustic devices. Helium's velocity of sound is much higher than that of air and helium will not condense or freeze at low temperatures. As mentioned the velocity of sound should be high. The thermal conductivity should be high as well, and the Prandtl number low, since a low Prandtl number would mean low viscous losses.

B. Acoustic Driver

The total acoustic power used by the refrigerator is provided by an acoustic driver. A significant portion of this power is used to pump heat in the stack and the rest is dissipated in different parts of the refrigerator. A higher performance of the driver leads to a higher performance of the whole refrigerator system. The accoustic driver converts electric power into accoustic power. The most common loudspeaker is of electrodynamic type which uses copper wires and permanent magnet. A loudspeaker with maximum power of 10 watts and 5Ω at the operating frequency of 360 Hz was selected as the acoustic driver for this study.

C. 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 [5]. The length of resonator tube corresponds to quarter of the wavelength of the standing wave is:

$$L = \lambda / 2 \qquad (2.1)$$

and

$$\lambda = a / f \qquad (2.2)$$

Where, *a* is the speed of sound, λ is the wavelength and *f* is the resonance frequency. The viscous and thermal relaxation dissipation losses take place within the distance equal to the thermal penetration depth, from the surface of the resonator. For the resonance frequency 360Hz, the length of resonant tube was set equal to 240 mm that corresponds to the quarter wavelength of the acoustic standing wave, the diameter of the resonator tube was set equal to 20mm.

D. Stack

The stack can be used to convert heat into acoustic power as well as the opposite, The amount of heat that can be converted into acoustic power (and vice versa) depends on certain aspects of the stack like material properties, stack dimensions and the position of the stack in the tube. Figure (5) Shows a stack. The stack material should have a high heat capacity and high thermal conductivity in the *y* direction. The thermal conductivity in the *x* direction however, should be very low.Heat pumping requires the heat storage and this requires high thermal conductivity in the *y* direction to be accessible. A low thermal conductivity in *x* direction is necessary to minimize losses through conduction from hot to cold side. As it becomes clear, a material with anisotropic thermal conductivity would be best. The length is important for the temperature gradient. The length and cross-sectional area of the stack also determine how much the sound waves are perturbed.

E. Modelling using DeltaE and Linear Approximations

For modelling and predictions on the behaviour of thermo acoustic devices DeltaE software is used in conjunction with the approximations. DeltaE is the short form of Design Environment for Low-Amplitude Thermo Acoustic Engines, is developed at Los Alamos National Laboratory. This software can perform calculations on all kinds of acoustic devices using a numeric approach. A text-based model of a device is built out of different segments. These segments can be a tube, a heat exchanger, stack, speaker, etc. The segments are written in sequence, corresponding to the actual location of each part of the device. A set of guessed and target values have to be chosen by the user to decide which variables need to be computed and which conditions must be fulfilled. DeltaE tries to reach the targets by changing the values in the guessed values. The guess values have to be chosen within an acceptable range for the solution to converge. An initial model is mainly based on rough estimates and certain constraints. With those estimations and constraints, DeltaE can do initial calculations and based on those results, the user can further change and optimize the model.

III. Fabrication

The components of the thermo acoustic refrigerator are designed, and the design parameters are selected as discussed earlier. Some standard components of the thermo acoustic refrigerator were purchased and some were fabricated are described below.

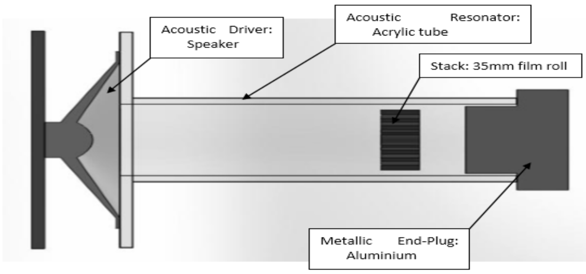

Fig .1 Schematic of Thermoacoustic Refrigerator

A. *Acoustic Driver*

The loudspeaker was driven by a function generator and a power amplifier to provide the required power to excite the working fluid inside the resonator. Efficiency of this type of loudspeaker is relatively low, and their impedances are poorly matched to gas when pressure inside the resonator is high.

Fig. 2 Acoustic Driver – Loudspeaker

B. *Acoustic Resonator*

The acoustic resonator was built from a straight acrylic tube of length 24 cm. the internal diameter of the tube was 20 mm and the thickness of the wall was 2.5mm. One end of the tube has an acrylic plate attached to install the speaker frame. At the other end, a stopper or plug made of Aluminium was placed inside the resonator.

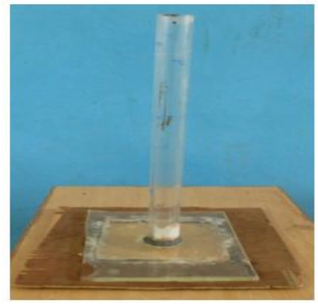

Fig. 3 Acoustic Resonator

C. *Stack*

If stack layers are too far apart the gas, cannot effectively transfer heat to and from the stack walls. If the layers are too close together, viscous effects hamper the motion of the gas particles. To construct the stack, a roll of 35mm film was unrolled. Lengths of fishing line were glued across the width of the film at equal intervals using a spray adhesive. To keep lines straight the line was first wound onto a ‘‘loom,’’ a cardboard frame with slits cut every 5 mm. After spraying the glue onto the lines, the frame was placed over the film and a Teflon weight was placed on top, to press the lines against the film. Once the glue was set, the fishing line was cut flush with the edges of the film. This process was repeated for approximately 1meter of film. The film was then rolled around a small diameter acrylic rod and layers were gradually peeled off until the film roll fit snugly into the tube. The stack was positioned in the tube approximately 4 cm from the closed end so as to be close to the pressure maximum, finally we get a stack as shown in fig.5.

Fig. 4 Stack

D. *End Plugs*

To make the resonator end closed we have used an Aluminium plug as shown in figure 6 to close the top end of resonator. As it forms the end of the hotter region in the resonator, a metal like

Aluminium was chosen to absorb this heat and dissipate it to the environment.

Fig. 5 End Plug

E. Assembly

It consists of an acoustic driver housing, an acoustic driver, stack, a resonator filled with air at atmospheric pressure and End plug. Two holes were made in the End plug to place the thermocouples at the upper end and cooler end of the stack. Two O-rings were used at both the ends of the resonator tube to seal it.

F. Thermocouples

J-type thermocouples were used for the temperature measurements in this study. They were used to measure the temperature at different locations inside the resonator.

G. Digital Temperature Indicator

An electronic temperature indicator with LED display was used to display the temperature readings from the thermocouples.

H. Panasonic Amplifier system

To generate the sound of frequency 360Hz from the acoustic driver unit we have connected it to the Panasonic Amplifier system that can playback the sound track of 360 Hz constant frequency.

IV. Experimentation

Schematic of the entire experimental setup is as shown in figure 7.

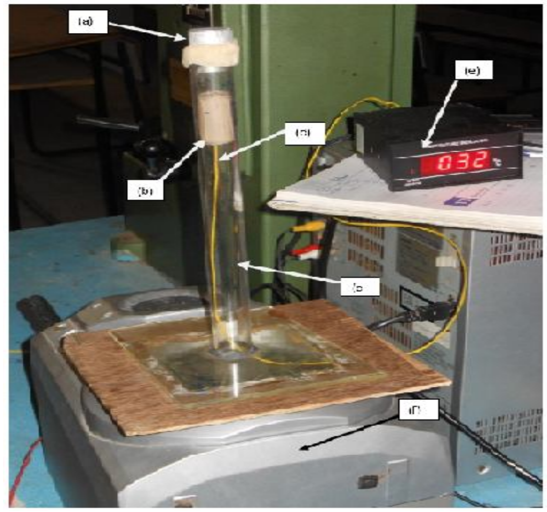

Fig. 6 Experimental setup
(a) End-plug (b) Stack (c) Acrylic Tube (d) Thermocouple
(e) Temperature Indicator (f) Speaker

The experimentation Procedure is as described below:

1. A sound track that has the playback of 360 Hz constant frequency sound is played in a music player these signals are sent to the amplifier unit which amplifies its power input of the speakers in the thermo acoustic refrigerator.
2. The temperature and time measurements are made with Thermocouples and Stop watch for the following cases:

- Measurements inside the resonator without stack
- Measurements inside the resonator with stack and without insulation
- Measurements inside the resonator with stack and insulation

V. Results and Discussions

The experimental results will explain about the effect of stack and insulation around the resonator on the Thermo Acoustic Refrigerator.

A.Temperature distribution in the resonator tube without the stack

This experiment is carried out without incorporating the stack. The temperature at different points inside the resonator along the length of the resonator was measured by using thermocouples. The thermocouples were placed inside the resonator and readings were taken for 205 seconds. The change in temperature along the length of resonator is shown in the graphical plot below figure 8.

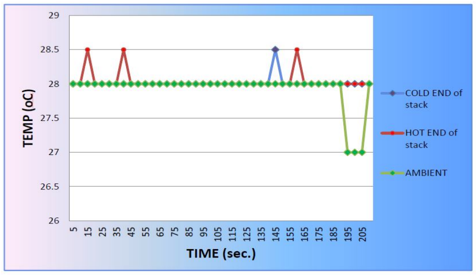

Fig.7 Temperature distribution at a point in the resonator without the stack

The graph shows that the temperature at all the points remained almost constant and did not change with time. The maximum variation in the temperature along the resonator tube was less than 0.5^{O}C.

B. Temperature distribution in the resonator tube with the stack

In this the temperature field inside the resonator tube was measured with the stack, in the presence of the acoustic standing waves.. The temperature at different points inside the resonator along the length of the resonator was measured by using thermocouples. The thermocouples were placed inside the resonator at both ends of stack and readings were taken for each position of stack for a time-period till the temperature at both the ends of stack become constant. The changes in temperature with time for a position of stack are as shown in the graphical plots below (figures 8 to 11). When the speaker was turned on, the standing acoustic wave was created inside the resonator, and thermo acoustic process was initiated. Once the thermo acoustic process starts, the parcels of air start transferring heat from the cold end of the stack to the hot end. As a result, the temperature at the cold-end of the stack started to decrease and the temperature of the hot-end of the stack started to increase. The largest temperature difference was observed between the two ends of the stack. A temperature difference as high as 15^{O}C was achieved across the stack approximately 300 seconds after the beginning of the thermo acoustic process.

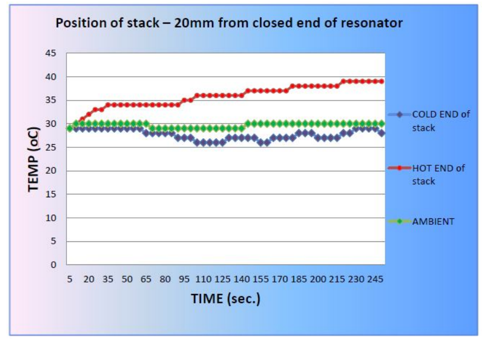

Fig. 8 Temperature distribution at a point-20mm from closed end of resonator with the stack

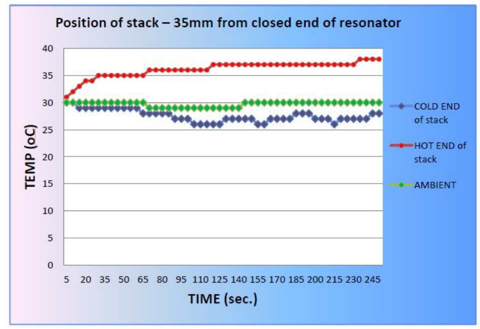

Fig. 9 Temperature distribution at a point-35mm from closed end of resonator with the stack

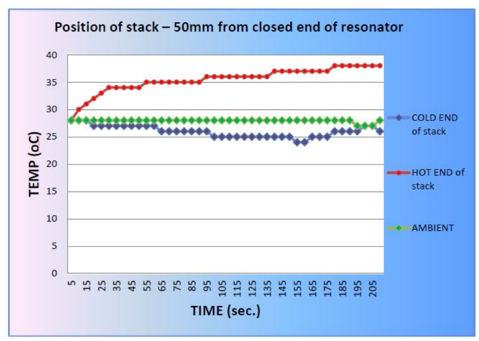

Fig. 10 Temperature distribution at a point-50mm from closed end of resonator with the stack

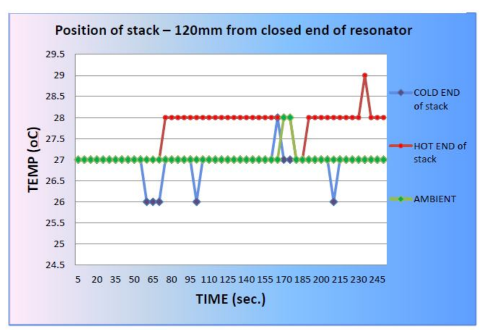

Fig. 11 Temperature distribution at a point-120mm from closed end of resonator with the stack

C. Stack position in the resonator tube for Maximum Temperature Difference

The position of stack inside the resonator is crucial for the optimum performance of the thermo acoustic refrigerator. (The power input to the speaker and operating frequency remained constant during experiments). The temperature difference across both side of the stack was measured in each experiment for 245 seconds and is plotted in fig. 12 against the stack position. The plot shows that as the stack position changed from 120mm to 50mm (i.e. close to a pressure antinodes), the temperature difference (ΔT) increased from $3^{O}C$ to $15^{O}C$. Further change in the stack position resulted in a decrease in the temperature difference. It shows that the optimum value for the position to get maximum temperature difference is 50mm.

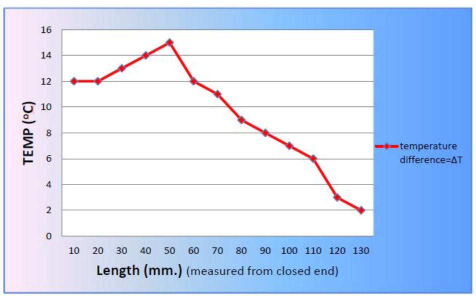

Fig. 12 Stack position, versus the temperature difference across the stack

B. Effect of insulation around the resonator of Thermo acoustic Refrigerator

It was observed during the experiment that heat flow into the resonator tube at the cold end of the stack affected the net cooling power of it. As heat flow into the region would lead to increase in temperatures thus reducing the cooling effect. To reduce such a loose due to thermal conduction from the walls of resonator we have conducted tests by providing Styrofoam insulation around the resonator. The experiments which were earlier carried out were again repeated for the frequency of 360 Hz and the temperature difference between the stack ends is measured [7]. These temperature difference with and without insulation is as shown in figure 13. The plot indicates that there is only a very small change in the temperature difference between the stack ends for with insulation and without insulation.

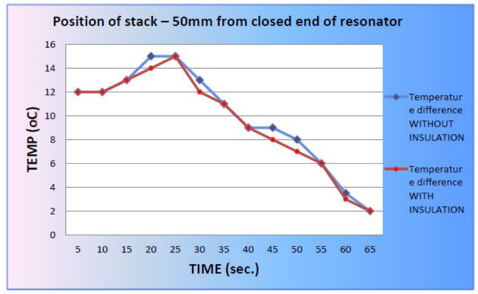

Fig. 13 Comparison of Temperature Difference for test runs without and with insulation.

VI. Conclusions

The results have shown that the performance of the refrigerator depends on the working gas, pressure inside the resonator tube, shape of the resonator tube, material, position and length of the stack. Another merit of this device is that it could provide cooling and heating simultaneously, that is cooling from the cold-end and heating from the hot-end. Based on the results of the present investigation the following conclusions may be drawn:

1. Without the stack the temperature along the resonator tube is almost constant the variation is within $0.5^{O}C$.
2. Temperature distribution along the resonator is significant effected by the presence of stack. After nearly 300 seconds of operation a temperature gradient of $15^{O}C$ was established across the stack.
3. The position of the stack is important in order to get maximum temperature gradient across the stack. For the resonator of 24cm the position of stack for maximum temperature around $15^{O}C$ gradient across the stack is 5cm from the closed end.
4. The power input is important to get the maximum temperature gradient across the stack; therefore an efficient acoustic driver is very important to get better COP.

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