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Demonstration of Thermo Acoustic Refrigeration by Setting up an Experimental Model

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ABSTRACT: *Conventional refrigeration techniques have high energy costs and continue to generate greenhouse gasses. One possible alternative could be thermo-acoustic refrigeration technology which is nascent, environment friendly and has benefit of no moving part. Thermo-acoustic is a combined branch of acoustics and thermodynamics which studies the transfer of heat by sound waves. The Thermo-acoustic refrigerator(TAR) uses sound energy to achieve refrigeration. A prototype was designed, fabricated and tested for exploration of this field and to demonstrate thermo-acoustic effect. For the design,standing wave and a quarter wavelength resonator with air as working fluid at ambient condition was used.Possible modification in design has been discussed to improve efficiency of TAR model.*

Keywords: *Thermo acoustic, Design, Refrigeration, prototype, sound Energy.*

I. INTRODUCTION

Refrigeration is the science of producing and maintaining temperatures below that of the surrounding atmosphere. It finds application in almost all fields for the purpose of temperature control. Until the beginning of the twenty-first century, CFC'S were widely used as refrigerants. The use of CFC's is banned acknowledging its harmful effects on the environment. This led to the evolution of HCFC's and HFC's. However these too have disadvantages. Both have high cost of production and contribute to global warming. The development of alternative cheap and green refrigeration techniques has thus become the priority for the future. Thermo Acoustic Refrigeration (TAR)is one such green idea for refrigeration. Lord Rayleigh was the first to give a thoroughly qualitative description of thermo-acoustic effects in 1887[1]. After this, the subject remained untouched until 1970 when scientists like Rott, Hofler and G. W. Swift signaled its revival with their research[2] on TAR.

Thermo-acoustic is a branch of acoustics and thermodynamics, which studies the movement of heat by sound waves. Acoustics deals with the study of effect sound transfer, like pressure changes and motion oscillations, whereas thermo-acoustic deals with temperature oscillations [3]. A basic knowledge of sound and heat transfer is a prerequisite for better understanding of the TAR.

Theory of Thermo Acoustics

From the basic physics of periodic sound waves[4], we get the equation for displacement:

$$s = s_{max} \sin (kx-\omega t) \quad (1)$$

and pressure

$$P = P_{max} \cos (kx-\omega t) \quad (2)$$

where,

k is wave number ,ω is angular velocity,$s_{max}$is maximum displacement amplitude and P_{max} is maximum Pressure amplitude.

From this, we can see that displacement and pressure are ninety degree out of phase

Swift showed that along with pressure there is also a temperature oscillation [2].The relation between the pressure of the adiabatic sound wave and its temperature is as given below [5].

$$T= C * P^{\frac{\gamma-1}{\gamma}} \quad (3)$$

where,

T is the temperature, C is a constant, P is the pressure and γ is the heat capacity ratio.

Consider a small parcel of gas oscillating back and forth over a small region. The pressure of the gas drops as it moves toward the pressure node, resulting in temperature drop. The effect is vice versa at the pressure antinodes. This is the basis of thermo-acoustic effect.

Principle of Working

Thermo-acoustics is a science that is concerned with the interaction between heat (thermo) and pressure oscillation in gases (acoustics).Working of thermo-acoustics can be broken into two categories. The first is the forward effect which is concerned with the generation of pressure oscillations from heat. This effect is primarily used to create engines that are widely referred as thermo-acoustic engines. The second subcategory or reverse effect is about using acoustic waves to pump heat. This reverse effect is primarily used to create refrigerators known as thermo-acoustic refrigerators.

Initially driver creates pressure oscillation inside the resonator in the form of sound waves. This causes temperature oscillation across stack through adiabatic compression and rarefaction of gas molecules near pressure antinodes and displacement antinodes in the resonator.

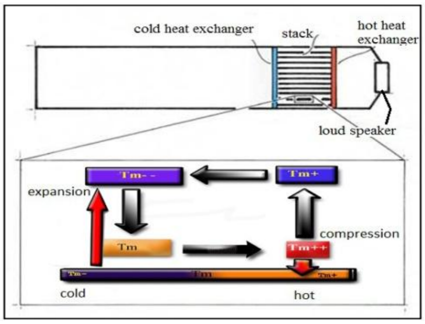

Fig.1 Working of Thermo-Acoustic Refrigerator

A magnified portion of the stack is shown in the fig.1. In order to simplify, we have considered a single stack plate. The plate is assumed to be at a mean temperature Tm.

The cycle can be explained in four steps.

The fluid or gas parcel is transported along the plate by oscillation produced by driver and at the same time it is heated by the adiabatic compression of gas from temperature Tm to Tm++.

This temperature of gas parcel (Tm++) is greater than plate at the extreme right end (Tm+). This temperature gradient causes flow of heat (Q) from the gas parcel to the plate.

After giving heat to the plate, the gas parcel is transported back to its original position by the reflected waves from the end and is cooled by adiabatic expansion to a temperature Tm--.

The temperature of the gas parcel (Tm--) is less than the temperature at the extreme left end of the plate (Tm-). Hence this temperature gradient causes the heat (Q) to flow from the plate to gas parcel and thus raising its temperature to Tm.

The net effect of this process is that it has completed a cycle, and an amount of heat Q has been transported up a temperature gradient, by work done in the form of sound. Heat exchangers are placed at both the ends of the stack in order to carry the heat from the specified area and transfer the heat plus work (enthalpy) to the atmosphere and cool the refrigerator compartment.

II. DESIGN AND FABRICATION OF TAR

The experimental model of TAR mainly consists of Resonator, Stack and Driver. Each component has been explained in the following sections.

Resonator

The purpose of the resonator in a TAR is to contain the working fluid and to cause it to have a desired natural frequency. Resonators are generally either half or quarter wavelength resonators. Quarter wavelength resonators are made with tubes by sealing one end and making the length approximately one quarter of the desired resonant frequency wavelength. The open end of the tube is simulated by attaching a large volume to the end. This large volume creates the boundary condition of zero pressure at the end. Quarter wavelength facilitates miniaturization of the model.

The resonator is needed to interface with the speaker and stack cross sections. Finally, it should be easy to manufacture. A simple tube can be used as the resonator. It makes calculation of the resonator natural frequency easy. At the driver end, the resonator is expanded to meet the speaker as shown in Fig.2. The other end is plugged with an aluminum cap as this is the hot end of the refrigerator and the aluminum would help heat to leave the system.

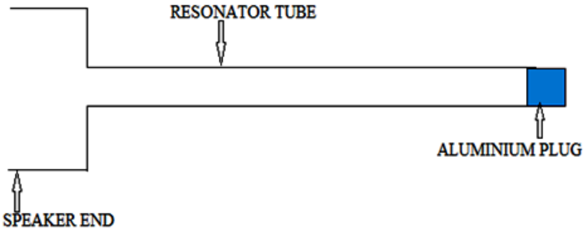

Fig.2A simple tube resonator design

The approximate resonator length for frequency of 400Hz is calculated as follows:
L= (velocity/4f) = 343/ (4×400) = 21.4cm.

Stack

Stack is the most sensitive part of the refrigerator, as small changes in stack dimensions can lead to huge changes in performance. It consists of large number of closely spaced surfaces aligned parallel to the length of the resonating tube. The stack material and thickness are important design considerations. A material that has a low thermal conductivity is desired because heat conducting across the stack works against the refrigerator. However, the material must also have a heat capacity much larger than the heat capacity of the working fluid so that sustained temperature gradient may be created. Mylar and camera film are some examples of materials used in the construction of stack.

Two important parameters for stack design are thermal penetration depth and viscous penetration depth. The thermal penetration depth is a metric describing how far heat can diffuse through the gas at the frequency driven. A fixed point will feel thermal effects from gas that is on the order of a thermal penetration depth away, but will not feel the effect of gas that is much further away.

The viscous penetration depth(δ_k)[6]is related to the distance at which viscous effects can be felt. When gas is oscillating past a surface, viscous drag will take place. As with the thermal penetration depth, gas that is on the order of a viscous penetration depth (δ_v)[6] from an object will experience viscous effects while gas that is much further away will not.

$$\delta_k = \sqrt{\left(\frac{k}{\pi.f.\rho.Cp}\right)} \qquad (4)$$

$$\delta_v = \sqrt{\frac{2\mu}{\omega\rho}} \qquad (5)$$

Where
δ_k=penetration depth, k = thermal conductivity of gas,ρ =density of gas, f= frequency,
C_p=isobaric specific heat and
δ_v=viscous penetration depth
The ratio of these two penetration depths is known as the Prandtl number σ

$$\sigma= \frac{{\delta_v}^2}{{\delta_k}^2} \qquad (6)$$

The variables that make up the thermal penetration depth are functions of the gas properties and the frequency. For the prototype, air was selected as working fluid. The properties for air at room temperature are,
$k = 0.0257$ W/mK, $\rho = 1.205$ kg/m^3, $C_p = 1005$ J/kgK.
Corresponds the above values,$\delta_k = 1.3\times10^{-4}$ m

Optimal placement for stack in the resonator is generally close to half way between the velocity and pressure nodes [5].Stack spacing is another important aspect of stack design. As the surface area within the stack is increased, the power density also increases because the thermo-acoustic effect takes place at the surface. However, if the surface area becomes too dense the thermal contact between the working fluid and the stack will be too strong which will prevent the thermo-acoustic effect from taking place.

Driver

The driver in a thermo-acoustic refrigerator is used to create acoustic waves. The frequency of wave created by the driver is generally at or near the resonant frequency of the resonator in which the wave oscillates. Driver operation is about 300-400 Hz.

Final Selection of Components

For resonator a PVC pipe of outer diameter 25.4 mm, 21.4 mm inner diameter having approximate length of 24 cm is selected. An Aluminum plug of 21.4 mm diameter and 60 mm length placed was placed for sealing the end of tube tightly and to dissipate heat from hot end of stack to atmosphere (Fig.3). The rod was machined on the lathe so that it could be fitted in the resonator. About 6.5mm of Al plug resides inside the resonator and rest outside so as to dissipate heat. Also, grooves were cut on its surface for higher heat transfer. For robust construction, Pioneer 4 inch diameter with 30W root mean square power and 4 ohm impedance driver was selected. For the driver casing a 150x150 mm wooden box was selected. The Amplifier for driving the speaker has to be of the same specifications. We selected a 50W power and 4 ohm impedance amplifier to provide required power to the woofer. A transformer of 38Volt, 5Ampere output was selected to integrate the normal power supply to that of the amplifier's. Coil design was selected for the construction of stack to reduce the difficulty in manufacturing. Neon optic line with a diameter of 0.35 mm was glued across the photographic film to enforce the spacing between the layers(Fig.4). The film was rolled up, after the glue dried (Fig.5). The diameter of the rolled up stack is 21.4 mm and its height is 35mm.

Fig.3The Aluminum plug

Fig.4 Construction of stack with photographic film and neon optic fiber

Fig.5 Stack used in thermo- acoustic refrigerator model

The placement of the top of the stack was selected to be 47 mm from the top end of the resonator so that it would be well placed between the velocity and pressure nodes. A wooden base plate was used create an interface between the speaker and the resonator. Finally, O rings and M seal were used for sound proofing at various sections of the apparatus.

III. EXPERIMENTAL SETUP

Model setup with the connection to data acquisition system (DAQ) is as shown in fig.6. Speaker was placed in the mount and the resonator on top of the speaker. For positioning the stack inside the resonator tube, it was slides from top end. It was pushed down until its top was 47 mm from the top of the resonator. For positioning thermocouples across the stack in the resonator tube, two small holes were drilled in the resonator. Thermocouples measure temperature of hot and cold end of stack. To seal the end of resonator tube aluminum cap was placed at the top of the resonator. For operation of TAR model a signal generator and transformer is required. Signal generator generates 400 Hz sinusoidal input signal to drive the speaker. Amplifier was used to bring the signal up to the desired amplitude. This amplified signal drives the speaker to create temperature gradient across the stack. Fig.7 shows the experimental setup in the laboratory.

The temperature difference was measured by the thermocouples placed at either end of the stack. The output from the thermocouples was given to data acquisition system (DAQ) for real time analysis

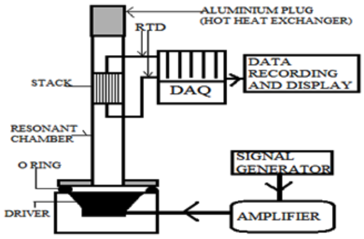

Fig.6 Set up for prototype testing

Fig.7 Experimental setup in the Laboratory

IV. RESULT AND DISCUSSION

The model was tested at 310 Hz natural frequency and approximately 10-15 watt power to display the Thermo-acoustic effect. Initially, the temperature at cold end reduced by 0.2058 degree Celsius in 10 seconds and then it began increasing. However the rate of increase of temperature at the cold end was very slow whereas the hot end temperature was rising at a faster rate(Table1).

This signifies that the Thermo-acoustic effect was taking place. However, the heat from the hot end, instead of getting dissipated by the heat exchanger into the atmosphere was actually flowing across the stack to the cold end, thus preventing the cooling effect from lowering the temperature. This is due to the various non-linearity present in the system due to which the heat exchange process was not taking place effectively. Using DAQ system the temperature difference obtained between hot end and cold end of stack was 5.5˚C. Temperature at cold end rose by 3.85˚C due to the reason explained above whereas temperature at hot end rose by 9.3˚C in 4 minutes.

V. CONCLUSION

The conclusion that we can derive is that the model was successful to demonstrate the Thermo-acoustic principle, however it could not demonstrate a distinguishable thermo-acoustic refrigeration phenomenon. The main reason for this was the heat exchange process. The heat from the hot region was not getting out of the system, thus getting accumulated in between the upper portion of the stack and the lower portion of heat exchanger. The transport of heat ends whenever it encounters asymmetry. In our model, air was occupying the space above the stack, which magnified this effect, due to which the heat was not getting transported further out of the system. This asymmetry could have been eliminated by providing individual heat exchangers at the two ends of the stack, instead of providing a single one at the top. These heat exchangers could have been made of copper wool and copper meshes having the same porosity as that of the stack. The same porosity would have helped to maintain symmetry at the stack-heat exchanger interface, thus preventing the accumulation of heat at the stack end.

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