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Experimental Investigation of Thermo Acoustic Effect Using a Thermo Acoustic Refrigeration Setup.

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Abstract *- The study of interaction of sound and heat is known as Thermo-Acoustic, where pressure fluctuations are coupled with unsteady heat release. However, in intense sound waves in pressurized gases, Thermo-Acoustics can be harnessed to produce powerful engines, pulsating combustion, heat pumps, refrigerators, and mixture separators. The generated acoustic wave can be effectively used for generation of refrigeration effect. The acoustic waves can be generated using an acoustic driver. This wave when made to travel in small channels known as Stack, oscillating heat also flows in between the channel walls. The combination of all such oscillations produces a Thermo-Acoustic e ect. These interactions are actually too small, but if developed can be effectively used to overcome drawbacks of conventional refrigeration system. The aim of this project is to study Thermo-Acoustic phenomena suing a Thermo-Acoustic refrigeration setup. The setup consists of acoustic driver (loudspeaker), resonator, stack and testing system. The stack and resonator design is based on Linear Thermo-Acoustic theory. Due to the large number of design parameters, a choice of some design parameters along with dimensionless independent variables has been introduced and explained. The manufacturing of the di erent components of the apparatus has been explained along with the reasons for using specific materials. Air at ambient pressure is used as a working fluid. Optimization of stack for its position in the resonator tube is carried out using MATLAB©. The performance optimization is carried out on the basis of the mathematical and experimental results obtained to minimize losses in the setup. The setup shows temperature differential across the stack ends. This setup could be used or incorporated with portable refrigeration system where operating temperature is not low as compared to the room temperature.*

Keywords — Thermo-acoustic, Stack, Resonator tube, Acoustic driver.

I. INTRODUCTION

Thermo-Acoustic is the study of the interaction between heat and sound. The term has lately become narrower in its meaning so that it refers mostly to the field applied to heat engines and refrigerators. Due to ease in computation with the development of advanced numerical solution software a resurgence of interest in this field has led to many advances in theory and experimental methods. 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. The technology has seen rapid growth since then developing into a promising asset as a clean and environmentally friendly refrigeration method. It has been realized that Thermo-Acoustic technology could be used particularly for refrigeration. The major advantages in comparison to standard vapor-compression refrigerators is that it is eco-friendly and the power requirement to run it is low. However for every-day refrigeration applications the technology is currently not capable of competing with existing one's because of their low COP and their low efficiency. But, it is possible that these drawbacks can be resolved through specific research efforts and in fact there is a growing interest in the research community to make these devices more competitive

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A. BASICS OF THERMO ACOUSTIC REFRIGERATION

Thermo-Acoustic refrigerator (TAR) is a special kind of device that use energy of sound waves or acoustic energy to pump heat from low temperature

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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'.

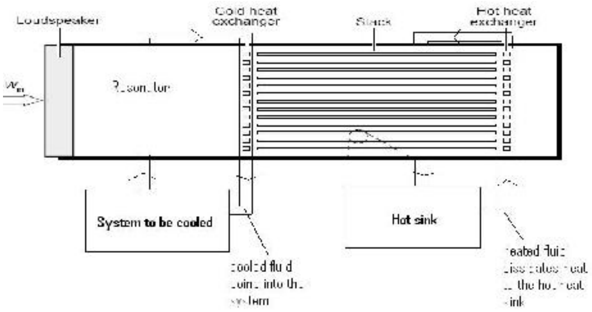

Fig -1 Schematic Diagram of Thermo-Acoustic Refrigerator

The frequency of the driver and the length of the resonator are chosen so as to get a standing sound wave in the resonator [1]. A solid porous material like a stack of parallel plates is kept in the path of sound waves in the resonator. Due to Thermo-

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.

B. DESIGN CONSIDERATIONS

Some assumptions were taken while designing the TAR. These were taken so that computation becomes easy. These assumptions were taken so that the various differential equations can be converted into relation between the dimensionless parameters.

1) *The boundary layer approximation*

The plate half-spacing yo within the Thermo-Acoustic stack is larger than the viscous and thermal penetration depths.

$$y_o > \delta_v \text{ and } y_o > \delta_k.$$

$$\delta k = \sqrt{\frac{k}{\pi\, \rho\, Cp\, f}}$$

$$\delta v = \sqrt{\frac{\mu}{\pi\, \rho\, f}}$$

2) *The short stack approximation*

The overall length of the Thermo-Acoustic stack and the heat exchangers is small in comparison to the length of the acoustic wave. Di erences in gas pressure and velocity are negligible over the stack length and the stack does not disturb the acoustic field.

3) *Temperature Difference*

The temperature di erence over the stack is assumed to be much smaller than the average gas temperature, so that the caloric properties of the working gas remain constant within the stack.

4) *Heat Coduction*

The heat conduction along the stack's x-axis is negligible for typical stack materials with low thermal conductivity

II. DESIGN OF EXPERIMENTAL SETUP

Design of experimental setup is mainly consists of the selection of working medium, design of stack, selection of stack material, the position of stack in the resonator tube and the selection of appropriate driver.

A. *Working Medium*

The working gas should have a large thermal penetration depth, δk, and a small viscous penetration depth, δv. A large thermal penetration depth allows for more heat transfer between the stack walls and the gas, increasing the overall efficiency of the TAR. A small viscous penetration depth indicates that losses per unit area due to viscous effects will be lower, which is important in the many small pores of the stack where the surface area is large. The thermal and viscous penetration depths are related by a fluid's Prandtl number, defined as,

$$Pr = \frac{{\partial_v}^2}{{\partial_k}^2}$$

Ideally Helium (He) would be the best suitable working fluid since it has low Prandtl number (Pr = 0.68) and have large value of specific heat index (γ = 5/3, as it is monatomic) [2]. Since the availability of Helium is an issue and also proper sealing is required to work with Helium gas as it leaks easily hence it was decided to use AIR as our working medium. Mean pressure, p0, is proportional to the power density of a Thermo-Acoustic refrigerator. For this reason, it is desirable to choose a large average pressure for maximum heat transfer. But working at higher pressure requires air-tight and

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leak proof setup. Therefore the working pressure was decided as 1 atm.

The drive ratio, D, should be kept sufficiently low so as to avoid acoustic non-linearities such as turbulence. Therefore,

$$D = 0.01$$

Thus, from boundary layer approximation and short stack approximation following results were obtained,

$$y0 = .3mm$$

$$y0 = 1.5\delta k$$

$$\delta k = .3/1.5 = 0.2mm$$

$$f = 179.279\ Hz$$

B. Stack

The Thermo-Acoustic stack can be considered the central part of the entire device. Generally, it consists of a solid with a large number of thin gas channels (pores) as shown in Fig-2. While the thermodynamic cycle process takes place, the solid is supposed to store heat temporarily without allowing for significant heat conduction along its x-axis.

The stack must be able to efficiently convert the acoustic pressure oscillations into a temperature gradient. It is desirable for the stack material to have a low thermal conductivity and greater heat capacity than the working gas. Low thermal conductivity is required since it will prevent heat flow across the stack through conduction.

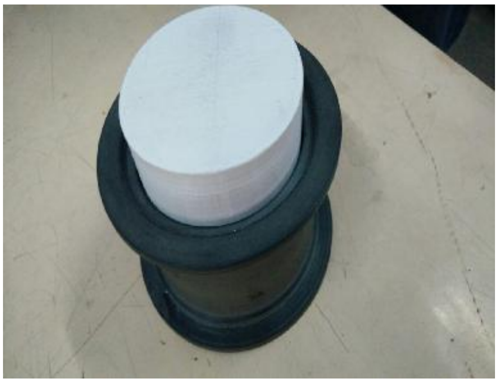

Fig-2 Stack

1. Stack Material

The material chosen should have a low thermal conductivity. As a TAR's main purpose is to move heat from one end of the stack to the other, heat conduction in the opposite direction (from the hot end to the cold end) results in a reduction of efficiency. The material should also have a larger specific heat capacity than the gas.

The manufacturing required was precise and accurate as the plate size were thin and the plate spacing was very small. Hence Selective Laser Sintering (SLS) (3-D Printing) with the material PLA was chosen to obtain accurate results.

2. Stack Length and Position

With a known frequency of operation, dimensionless heat and work flow equations were used to calculate and plot performance curves for various stack lengths and positions relative to the speaker. These equations were derived from the exact partial differential equations by making some simplifying assumptions. The dimensionless form of these equations, as derived by Tijani et al.[3] were used for the design process.

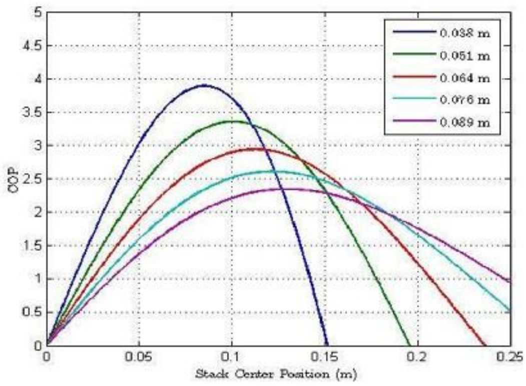

Fig-3 Co-efficient of Performance vs. Stack Centre Position

Since it was difficult to find the values of the differential equation having so many parameters graphs were plotted in MATLAB© as shown in

Fig-3 and the acquired values were used in the differential equations [4].

From the graphs plotted, the stack length was found to be,

$$Ls = 0.06m$$

Now for a stack length of 0.06 m the maximum achievable COP is about 2.9 and corresponds to a stack centre position of x_s = 0.112 m from the speaker face.

C. Resonator Tube

The resonator is designed in order that the length, weight, shape and the losses are optimal. The resonator has to be compact, light, and strong enough. The shape and length are determined by the resonance frequency and minimal losses at the wall of the resonator. The cross-sectional area A of the resonator at the stack location (Fig-4) is determined according to available PVC pipe since cooling power wasn't decided. The acoustic resonator can have λ/2- or a λ/4length.

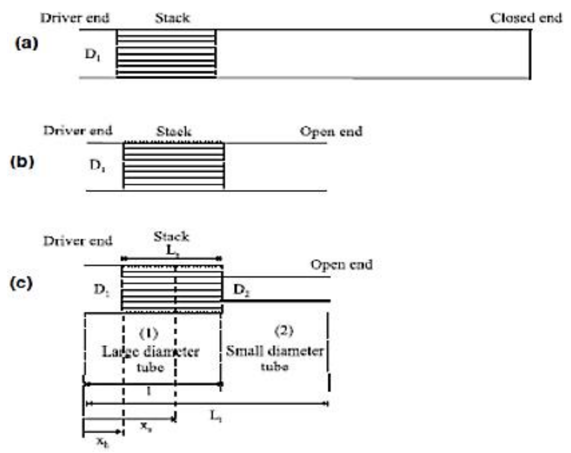

Fig-4 Stack Location

There are two ways to minimize the surface area of a standing wave TAR that have been widely used. The first is to make use of the quarter-wavelength resonator geometry and the second is to reduce the resonator diameter at the cold end of the stack. This geometry is called a Hofler resonator. The open end of an ideal quarter-wavelength resonator cannot contain pressures above 1 atm, so the boundary condition at that end must be simulated with an enclosed buffer volume. As a result, the resonator will be somewhere between a quarter- and half-wavelength

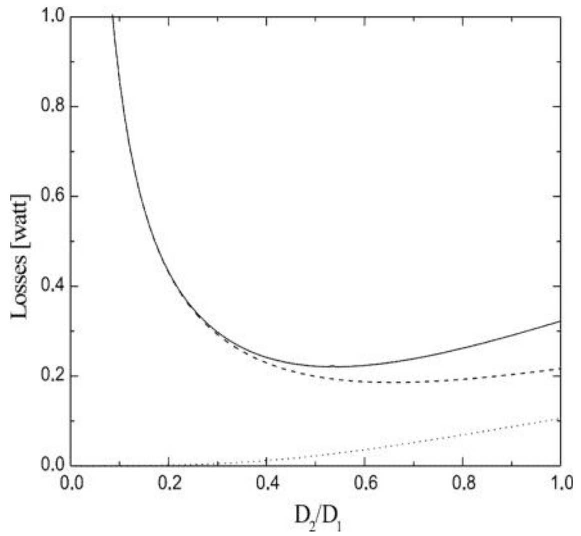

Fig-5 Thermal Losses v/s D_2/D_1[1]

The thermal loss increases monotonically as function of the ratio D1/D2 as shown in Fig-5, but the viscous losses decrease rapidly up to about D1/D2 = 0.5 and then increase slowly. As a result the total loss (sum) has a minimum at about D1/D2 = 0.54. This was taken as a direct result from the work of Tijani[1].

The buffer volume size can be determined by matching its impedance to the end of the small diameter tube. Because PVC fittings are available only in certain standard sizes, it was difficult to make an accurate buffer volume without modifying parts and, therefore, compromising the structural integrity of the resonator. It was assumed that a buffer volume at least as large as the volume of the rest of the resonator would sufficiently approximate the open-end condition required for a quarter-wavelength resonator.

D. Driver

In experimental TAR designs in the literature, the drivers are often highly modified HiFi speakers or specially designed acoustic drivers for thermos-acoustic applications which are perfectly matched to the acoustic system in terms of moving mass, sti ness, B×L product, etc[5]. The reason is that commercial HiFi-speakers have a comparably low electro-acoustic conversion e ciency (usually a few percent) because they are optimized for operating at a broad range of frequencies. Due to their low e ciency, they produce a lot of waste-heat which additionally perturbs the thermo-acoustic system. In TAR designs which use pressurized vessels, the e ciency of the driver can often be increased by including a gas-spring in the back of the speaker. However, for ambient pressure, the gas spring's required piston area would drastically exceed the cross-sectional area of the entire resonator. Therefore, a commercial HiFi speaker was best suitable for this experimental setup and selected.

III. MODELLING OF THE RESONATOR TUBE

The modelling was done keeping in mind the Linear Thermo-Acoustic Theory with all the necessary assumptions and design calculations. The overall length of the resonator tube including the buffer volume was taken as 750 mm. The length of the large diameter tube or the hot duct after calculation was taken as 190 mm while that of small diameter tube or the cold duct was taken as 210 mm.

Fig-6 Modelled resonator Tube

After deciding the diameter ratio due to thermal losses, the diameter of large diameter tube and the small diameter tube was taken as 84 mm and 45 mm respectively. To have a modular design and easy removal and interchanging of parts, they were either given press fit or a threaded joint of M58x1.5 – 6g which are used for denoting the Pipe threading. The modelled resonator tube is as shown in Fig-6.

IV. EXPERIMENTAL RESULTS.

The assembly of the thermo acoustic refrigeration setup is done as shown in Fig-7.

Fig-7 TAR Experimental setup.

The hot end and the cold end of this setup was connected to DAQ system using J-type thermocouple. The DAQ 9219 was used for measuring the temperature. Both the waveform chart and numeric data was found at particular intervals of time and following temperature variation were observed.

The experimental results obtained are shown in the Table-1

Table-1 Experimental Results

Time (Seconds)	Temperature in °C	
	Hot end temperature (°C)	Cold end temperature (°C)
0	32.93	32.29
10	32.47	32.22
20	32.92	31.91
30	33.4	31.76
60	34.84	30.69
120	36.28	29.93
180	37.86	29.92
300	39.65	29.36
480	42.82	29.45
600	44.01	29.78

V. CONCLUSION.

The maximum cold end temperature was 29.36°C which is a drop of approximately 3°C from the room air temperature. Also the temperature differential across the ends of stack grew consistently. Maximum temperature differential of 14.2°C was observed at 10 minutes.

From the obtained results the following observations were made regarding the temperature drop and working of TAR.

- Initially the temperature drop is quite slow as the heat transfer across the stack takes some time. After the heat flux transfer is set up the rate of temperature drop increases.
- Ideally the increase in temperature at hot end and decrease in temperature at cold end should be same. But we can see that initially the difference was approximately same but as the time progressed the temperature of the hot end rose sharply. Also after 5 minute we can see that temperature of cold end becomes steady while the hot end temperature continues to increase.

- This happens because of convective and conductive heat transfer taking place within the resonator tube across the stack.
- However with the increase in the hot end temperature and near constant cold end temperature we could conclude that the Thermo-Acoustic effect was taking place successfully. Ideally cold end temperature should also go down, but since proper heat transfer wasn't taking place the temperature became constant.

After running it for more than 10 minutes we observed that that the cold end temperature rose sharply. This was because of heat exchanger not working properly and various non-linearity in the system.

From the above results, it can be concluded that the Thermo-Acoustic effect was successfully set up. But the temperature rise was faster on the hot side of the stack and the cold end temperature couldn't be maintained constant for more than 10 minutes. The main reason for this was the inefficient heat exchange process. The model was successful to demonstrate the Thermo - Acoustic phenomena; however it could not demonstrate a distinguishable thermo- acoustic refrigeration process.

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