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Design, Fabrication and Analysis of a Thermo-Acoustic Refrigerator

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***Abstract*— Thermo-acoustics deals with the conversion of heat energy into sound energy. Cooling devices based on the thermo-acoustic principal, pump heat using acoustic waves. The Thermo-acoustic refrigerators are simple, have no reciprocating parts and have no negative effects on the environment. On the contrary, vapor-compression systems are complex devices requiring preventive maintenance, along with having detrimental effects on the environment.**

This paper describes the fabrication and analysis of a simple thermo-acoustic refrigerator. The design of the fabricated model is based on the software simulation results of our former research work which delineate a numerical study and computer simulations carried out on a couple of software; DELTAEC and ANSYS Fluent. 2 new models were also constructed with the aim of increasing the effectiveness of the thermo-acoustic effect and all the 3 models were tested on various frequencies and three different power levels. The final experimental results were in line with the predictions of the software simulations and the new design models increased the effectiveness of the thermo-acoustic effect by a maximum of 93% percent when compared to the initial fabricated model.

***Keywords*— Thermo-acoustic, refrigerator, temperature, gradient, frequency.**

I. INTRODUCTION

Apart from Vapor compression cycle, there are several ways to provide cooling and refrigeration. One such technique involves using sound waves to achieve temperature difference, this phenomenon is known as Thermo-Acoustic Refrigeration. Thermo-acoustic is a science that is concerned with the interactions between heat (thermal) and pressure oscillations in gases (acoustics). There are two effects; the forward effect and the backward effect [2]. The forward effect deals with the generation of pressure oscillations due to application of heat which is used to create heat engines. The other effect produces temperature gradient using sound waves and is used in the designing of thermo-acoustic refrigerators. To demonstrate this phenomenon, we built a prototype refrigerator based on our previous simulation results [1].

II. FABRICATED MODEL DESIGNS

For the physical demonstration of the thermo-acoustic phenomenon a basic model with three different designs were constructed, comprising of following basic components:

Resonating Tube: It houses all the components and standing waves resonate inside the tube. Acrylic was chosen as the material of the tube mainly due to its low cost, easier availability, and workability. A frequency of 350 Hz and a quarter wavelength resonator design was selected, therefore the length of tube (OD = 3 cm) is calculated as;

$$L = \frac{velocity\ of\ sound\ in\ air}{4 * frequency} = \frac{340}{4 * 350} = 24.3\ cm \qquad \text{Eq (1)}$$

Acoustic Driver: The acoustic driver is a driving source of heat in a thermo-acoustic refrigerator. An electromagnetic speaker, with the rated power of up to 20W, was chosen mainly due to its easy availability and cost.

Stack: The stack is the portion where heat transfer takes place generating a temperature gradient. A spiral sheet stack was made with camera film and nylon fishing lines, as it is simple to construct while maximizing the surface area for heat transfer.

Working Fluid: Air at standard room temperature and pressure.

Temperature Data Logging: LM35 sensors connected to an Arduino microcontroller were used to record the hot and cold side temperatures of our thermo-acoustic refrigerator

A. Simplified Design

This is the most simplified model (Figure 1), to demonstrate the thermo-acoustic phenomenon, it uses an electromagnetic speaker coupled at one end of the tube and an aluminum plug on the other. The stack is placed at a calculated distance (5.2cm) from the tube's end. The LM35 sensors are placed at the opposing ends of the stack.

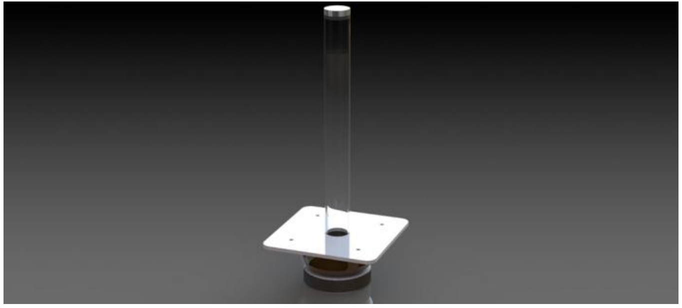

Fig. 1: Assembled TAR Rendered View

B. Stepping Reducer Design

This design consists of a stepping reducer form to maximize the transfer of acoustic energy into the resonating tube (Figure 2). The reducer diameter and length, at the speaker outlet are

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(10.16 cm, 5 cm), followed by (7.62 cm, 9 cm) and finally (5.08 cm, 4 cm) at the resonating tube inlet respectively.

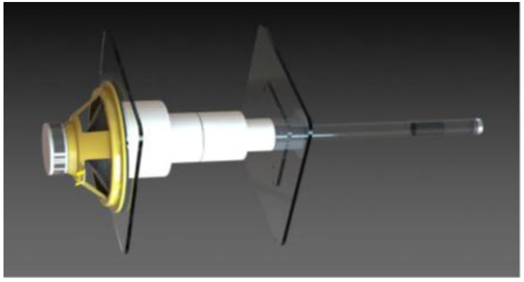


Fig. 2: Assembled Stepping Reducer Rendered View

C. *Tapered Reducer Design*

The tapered reducer (Figure 3) is a funnel that matches the diameter of the speaker at one end (17.8 cm) and tube outer diameter at the other end (3 cm). The tapered reducer is designed to transfer nearly all of the energy into the tube, though losses do occur. Its smooth taper allows the air particles to converge at the inlet of the tube, hence it is the most effective design amongst all other designs.

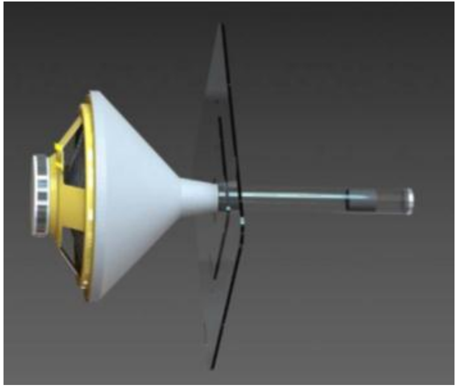


Fig. 3: Assembled Tapered Reducer Rendered View

III. TESTING, RESULTS AND DISCUSSION:

A. *Simplified Design*

The resonant frequency for this design (Figure 4) was 350 Hz though the design was tested over 10 different frequencies and three different power levels.

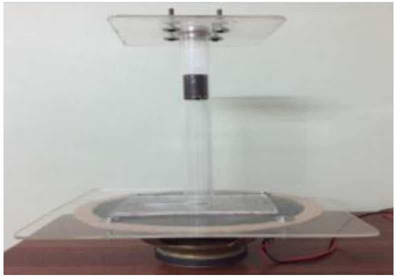


Fig. 4: Actual Fabricated Simplified Design Model

The maximum temperature gradient achieved across the stack was 7 K at 350 Hz at 6.3 Watts of input power (Figure 5), however as the operating frequency crosses 350 Hz the temperature gradient falls.

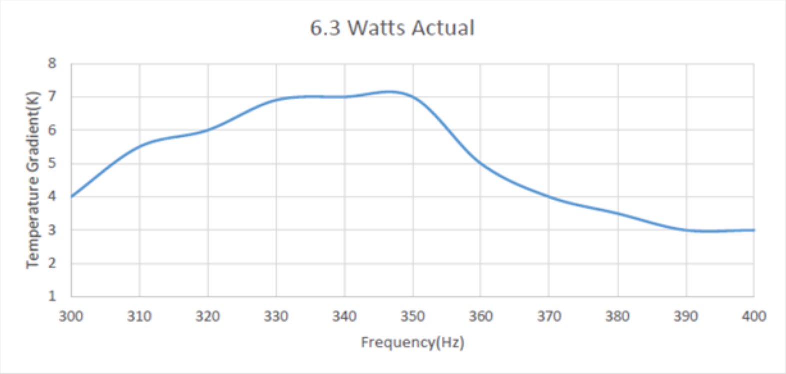
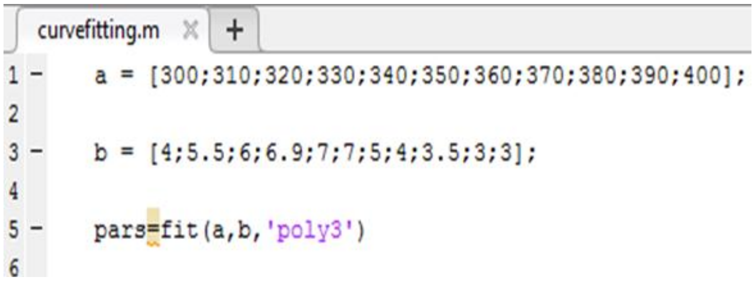


Fig. 5: 6.3 Watts Testing Curve

The graph (Figure 5) was analyzed using MATLAB and curve fitting techniques were used to construct an equation that can theoretically determine the behavior of our refrigerator over a range of operating frequencies. (Figure 6). The following equation (2) was obtained where T is the temperature gradient and f is the operating frequency.



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a = [300;310;320;330;340;350;360;370;380;390;400];

b = [4;5.5;6;6.9;7;7;5;4;3.5;3;3];

pars=fit(a,b,'poly3')

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Fig. 6: MATLAB Curve Fitting Code

$$T = 2.617 \times 10^{-5}(f^3) - 0.0286\,(f^2) + 10.33f - 1228 \qquad \text{Eq (2)}$$

Based on equation (2) a predictive graph (Figure 7) is plotted which closely resembles the actual graph. The approximation error in the equation above is within 14% percent of the actual values which is quite close, considering the turbulent behavior of the thermo-acoustic phenomenon. Hence the predictive graphs can be used to estimate the temperature gradient at any other frequency with less than 14% error on 6.3 Watts operating power.

At 14 Watts operating power, a temperature gradient profile was generated (Figure 8) with a maximum of 8.6 K achieved around 350 Hz.

At 20.1 Watts a temperature gradient of 12.1 K was achieved across the stack at 350 Hz (Figure 9)

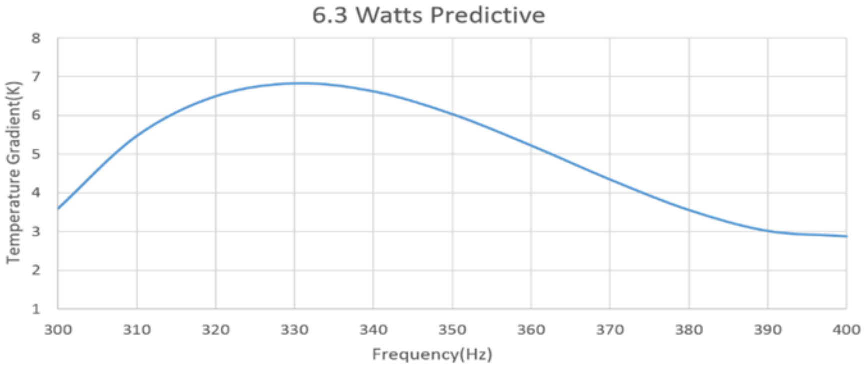

Fig 7: 6.3 Watts Predictive Curve

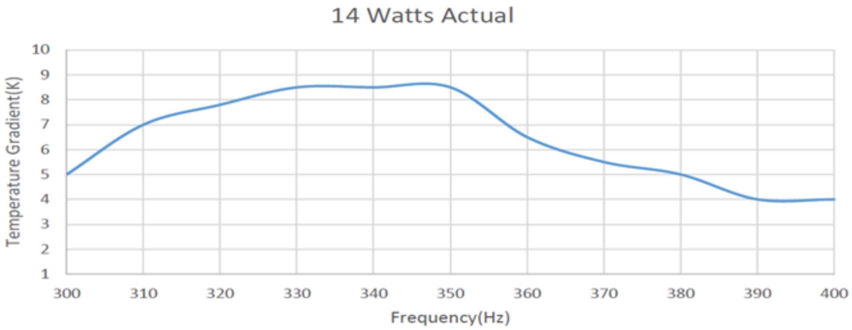

Fig 8: 14 Watts Testing Curve

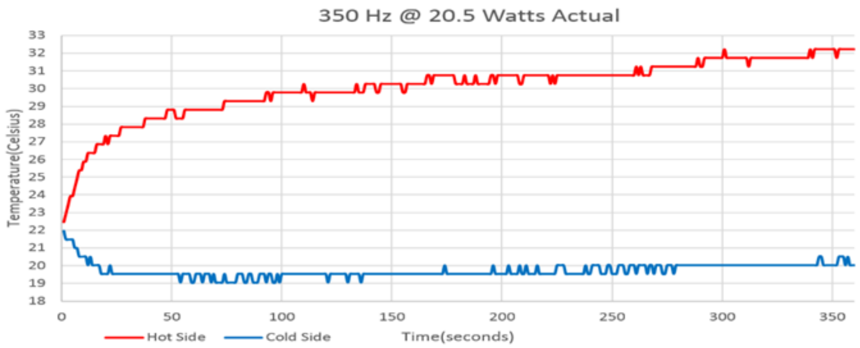

Fig. 9: Testing at 20.1 Watts, 350 Hz

B. Stepping Reducer Design

The stepping reducer design (Figure 10) was tested over three different frequencies and various power levels as specified in TABLE 1.

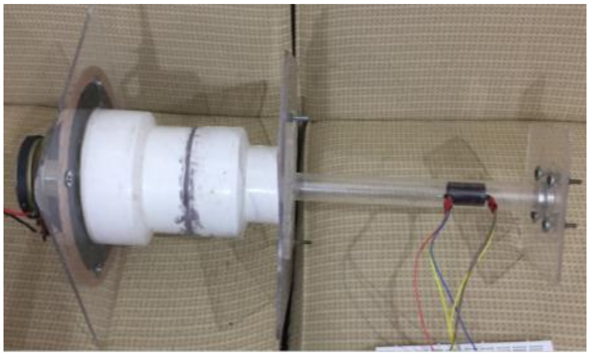

Fig. 10: Actual Fabricated Stepping Reducer Model

TABLE I: Stepping Reducer Testing

Testing Frequency	Input Power (W)	Temperature Gradient (K)	Comparison with Original Design
330Hz	6.3	9.8	42% increase
	14	11.3	33% increase
340 Hz	6.3	10.3	47% increase
	14	11.8	42% increase
350 Hz	6.3	10.8	54% increase
	14	12.6	48% increase
	20.1	14.2	16% increase

An increase of greater than 50% temperature gradient can be seen which reflects on the effectiveness of this design. The installation of reducers transfers maximum acoustic energy.

C. Tapered Reducer design

The tapered reducer design (Figure 11) was tested on three different frequencies and various power levels as specified in TABLE 2. For the tapered reducer design the resonant frequency was 340 Hz. The tapered reducer design was the most effective amongst all the designs. A temperature gradient of 16 K was achieved across the stack which is significantly higher when compared with the 12 K gradient achieved in the original design. The diameter of the reducer at the inlet matches the diameter of the speaker cone, similarly the outlet of the reducer is same as the outer diameter of the tube therefore it takes most of the acoustic input from the speaker and concentrates it at the inlet of the resonating tube, thus transferring maximum portion of the acoustic energy.

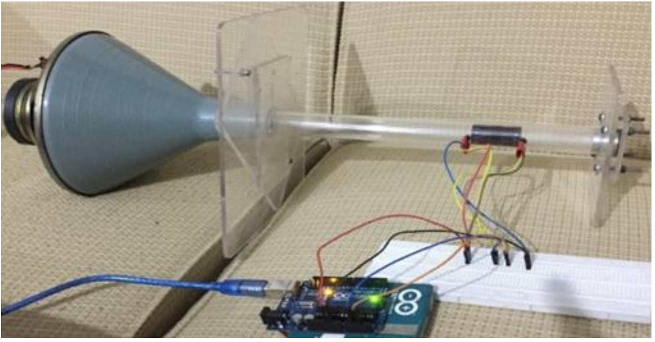

Fig. 11: Assembled Tapered Reducer Model

TABLE II: Tapered Reducer Testing

Testing Frequency	Input Power (W)	Temperature Gradient (K)	Comparison with Original Design
330 Hz	6.3	13.3	93% increase
	14	15.0	76% increase
340 Hz	6.3	12.8	83% increase
	14	15.2	79% increase
350 Hz	6.3	11.2	60% increase
	14	13.5	59% increase
	20.1	15.8	29% increase

Be sure that the symbols in your equation have been defined before the equation appears or immediately following. Italicize symbols (*T* might refer to temperature, but T is the unit tesla). Refer to “(1),” not “Eq. (1)” or “equation (1),” except at the beginning of a sentence: “Equation (1) is…...”

IV. CONCLUSION AND DISCUSSION

After extensive analysis through 45 tests runs; we achieved a temperature gradient of 12.21K at an input of 20.1 watts as predicted by our simulation software in our previous research work [1]. For analysis we tested our prototype over 10 different frequencies and 3 different power levels. We also tested for two additional designs; 1) Stepping Reducer Design 2) Tapered Reducer Design. For stepping reducer design, we achieved a maximum gradient of 14K for input power of 20.1 watts. For tapered reducer design we achieved a maximum gradient of 16K for an input power of 20.1 watts.

In our former research [1], we simulated the thermo-acoustic refrigerator model using ANSYS and DELTAEC to predict a temperature gradient of 12K for 18.75 watts of input acoustic power, in actual results we achieved 12.21K for 20.1 watts of acoustic power. The simulated result is almost identical to actual result. The actual power was only 7% greater as compared to the simulated power which accounts for the heat lost and gained from the surroundings.

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