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OPTIMIZATION OF THE DESIGN OF A PIEZOELECTRICALLY DRIVEN THERMOACOUSTIC REFRIGERATOR

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ABSTRACT

Thermoacoustic refrigeration is an emerging field of technology. This technology uses sound waves to pump heat across a temperature gradient and the sound waves are produced using a piezoelectric material. The design of a piezoelectrically thermoacoustic refrigerator are explained in detail. The effects of resonant frequency, resonator tube diameter, stack length, ambient temperature and working fluid have been studied. Graphs of the parameters' variation against the temperature gradient is plotted and maximum value is identified. Finally an optimum design is identified using the above results. Commercially thermoacoustic refrigerators are not in use, they are used only for research purposes. This paper aims at trying to obtain refrigeration effect without using any harmful refrigerants and without any moving parts through this piezoelectrically driven thermoacoustic refrigerator. Piezoelectric material usage reduces the overall cost since the alternative i.e. the electromagnetic speakers are comparatively expensive.

Key words: Thermoacoustics, Piezoelectric, Refrigeration, DeltaEC

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1. INTRODUCTION

Thermoacoustics is the science which deals with the interactions of heat (thermo) and pressure oscillations in gases (acoustics). It can be broken into two major subcategories which are the Forward Effect and the Reverse Effect. In the Forward Effect the pressure oscillations are generated from heat while in case of Reverse Effect the pressure oscillations generate heat (which is our main motive). The piezoelectrically driven thermoacoustic refrigerator works on the Reverse Effect. To understand the concept of pressure generation from heat, visualize a tube sealed at one end and open at the other end. The temperature goes on decreasing from the closed to the open end of the tube. When the closed end side is heated with a source (flame) a temperature gradient is developed as shown in the figure. The temperature of the channel is now more than that of the gas particles inside the tube because of the heat source. So, heat transfer takes place from the channel wall to the gas particles (heat transfer takes place from higher temperature to a lower temperature). Because of absorption of heat by the gas particles they expand and move towards the open end of the tube as towards the closed end there is no space available and the temperature at that end is also higher. So, the collective movement of the gas particles is towards the open end of the tube. As the particles move towards the open end of the tube the temperature of the channel wall goes on reducing (temperature gradient of the heat source) and there comes a point where the temperature of the gas particles inside is more than that of the channel wall surrounding it. Now the heat transfer takes place from the gas particles to the channel wall producing a cooling effect and results in the contraction of the gas particles along the temperature gradient of the channel wall. This results into creation of vacuum and causes the gas particles to move towards the closed end of the tube. This cycle goes on repeating and the movement of the gas particles to and fro from one end to the other results in generation of pressure waves.

Pumping heat using pressure waves is what the thermoacoustic refrigerator is based on. The Reverse Effect is literally the reverse of the Forward Effect. To get a better understanding of the Reverse Effect visualize a tube closed at one end (just like the one in Forward Effect) and on the other end there is a piston that can be actuated by electrical sources. The air inside is initially at rest. When the piston is actuated (usually by an AC source) it moves towards the left resulting in the gas particles being compressed towards the closed (left) end of the tube. This compression of the gas particles according to the ideal gas law results in slight increase in the temperature of the gas particles above the ambient temperature. Since the channel wall of the tube is still at the ambient temperature the heat transfer takes place from the gas particles to the surround channel wall. After some heat has been deposited on the channel wall the piston moves towards the right. This causes the volume to increase but since the number of gas molecules are the same the gas expands and this results in movement of gas particles to the right and cooling of the gas particles. The temperature of the channel wall is now more than that of the gas particles and hence heat transfer takes place from the channel wall to the gas particles. The piston is moved back to the left causing the cycle to repeat again and this rapid procession of the cycle causes heat to be moved from the right to the left.

2. DESIGN

2.1. Overview

The design of a thermoacoustic refrigerator is a growing field for research purposes. This part deals with the design of a thermoacoustic refrigerator and its basic components. There are four major components of a thermoacoustic refrigerator: driver, resonator, heat exchanger and stack. The driver provides the required sound waves to produce the reverse effect. The frequency produced is generally the resonant frequency of the resonator in which there’s a stack to provide more surface area for the heat transfer to take place. To maximise the temperature gradient available at the stack a heat exchanger is installed to utilise the heat generated at the stack portion. More efficient the heat exchanger better will be the utilisation of the heat available.

2.2. Driver

The driver of the thermoacoustic refrigerator is responsible for creating acoustic waves within the resonator tube. Usually electromagnetic speakers are used but when higher frequencies are desired piezoelectric material is often used. There are several things that need to be kept in mind to decide which speaker should be used. Firstly, the ratio $(Bl^2) / (R_e R_m)$ should be maximised where, "l" represents the length of the coil used to actuate the driver, "B" is the inductance of the coil, "R_e" is the electrical resistance of the driver and "R_m" is the mechanical resistance of the driver. Secondly, stiffness in the suspension of the driver should be chosen so as to make the combined mechanical and electrical impedances completely real for the operating frequency of the refrigerator. Thirdly, electroacoustic efficiency should be maximised by selecting a piston sized so that impedance matching between the mechanical and acoustic loads takes place. Finally, when the driver can't be altered the operating frequency can be adjusted so as to achieve impedance matching.

2.3. Resonator

The Resonator contains the working fluid in the thermoacoustic refrigerator and to cause it to have desired natural frequency. They are generally 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 an open volume at the end.

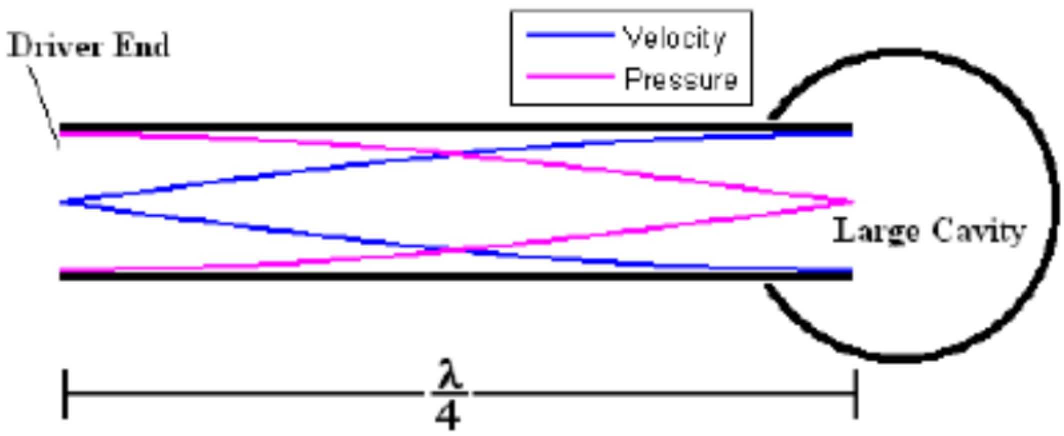


Figure 1 Resonator tube with quarter wavelength with large cavity at the end

This large volume creates the boundary condition of pressure node and velocity anti-node while the beginning of the resonator is a velocity node and pressure anti-node. This means that the natural frequency of such a resonator will have a wavelength four times the resonator wavelength from which quarter wavelength resonators derive their name. An example is shown in the figure.

Half wavelength resonators can roughly be compared to a tube that is closed at one end. The closed end means that the gas inside can't move and hence at the closed end there's a velocity node and pressure anti-node. The driver at the beginning also creates a pressure anti-node and velocity node, and hence it causes the natural frequency of such a cavity to be half the acoustic wavelength.

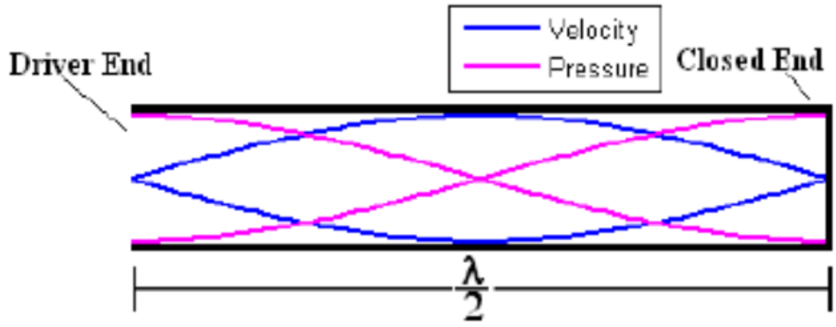


Figure 2 Resonator tube with quarter wavelength with a closed end

Real resonators are close to the ideal half or quarter wavelength ones as shown in the above figures but they are never the same as the ideal ones as they are hard to manufacture and are not always the best possible choice. Also, there's an assumption made that the driver also creates a pressure anti-node and velocity node at the open end of the resonator. The validity of this depends on the driver and also on how it is attached to the resonator.

2.4. Stack

Stack is the heart of the thermoacoustic refrigerator. The thermoacoustic effect takes place here and it is this part which changes the performance of the refrigerator as it is very sensitive to design and small changes result in vast changes in the performance of the thermoacoustic refrigerator. The major decision to be taken in stack design is the trade of between efficiency and cooling power. The reason of this trade of is that there's a point in the resonator where pressure and velocity both work towards the maximisation of the thermoacoustic effect but the cross section is so small that it will not produce any cooling effect if the resonator is operated in that region only. Now if the cross section area is increased the cooling power will increase but the efficiency will decrease since further the stack from the optimal point lesser is the efficiency. For every stack length there's an optimum placement point which is usually half way between the velocity and pressure nodes.

Another important aspect in stack design is the spacing. As the surface area increases the power density also increases because the thermoacoustic effect takes place at the surface. But care should be taken while increasing the surface area because if the surface area becomes too high the thermal contact between the working fluid and the stack will become too high and will prevent thermoacoustic effect from taking place.

Other important aspects that need to be considered are the material and the thickness. A material with low thermal conductivity is desired since a higher thermal conductivity material will conduct heat across the stack which will work against the thermoacoustic refrigerator. The material should have a high heat capacity, more than that of the working fluid as well to maintain the temperature gradient. The thickness should be sufficient to provide good heat capacity but at the same time care should be taken since more the thickness more will be the blockage caused by the stack plates. Above that more the thickness of the material more will be the formation of eddies at the ends of the stack which cause loss.

2.5. Heat Exchangers

Heat transfer for constant flows have extensively been studied but in thermoacoustic refrigerators the flow is oscillatory and heat exchangers design for such flows is challenging. They are made up of Copper and the cross section is made similar to that of the stack. The porosity is also the same as that of stack to maintain the velocity of the flow through the stack. It should be kept in mind that the length of the heat exchanger should be in the order of maximum displacement of the gas particles. Experiments conducted by various scientists conclude that the heat transfer coefficient of the heat exchanger is the maximum when the mean pressures are high and at the resonant frequencies where the dynamic pressure is maximum.

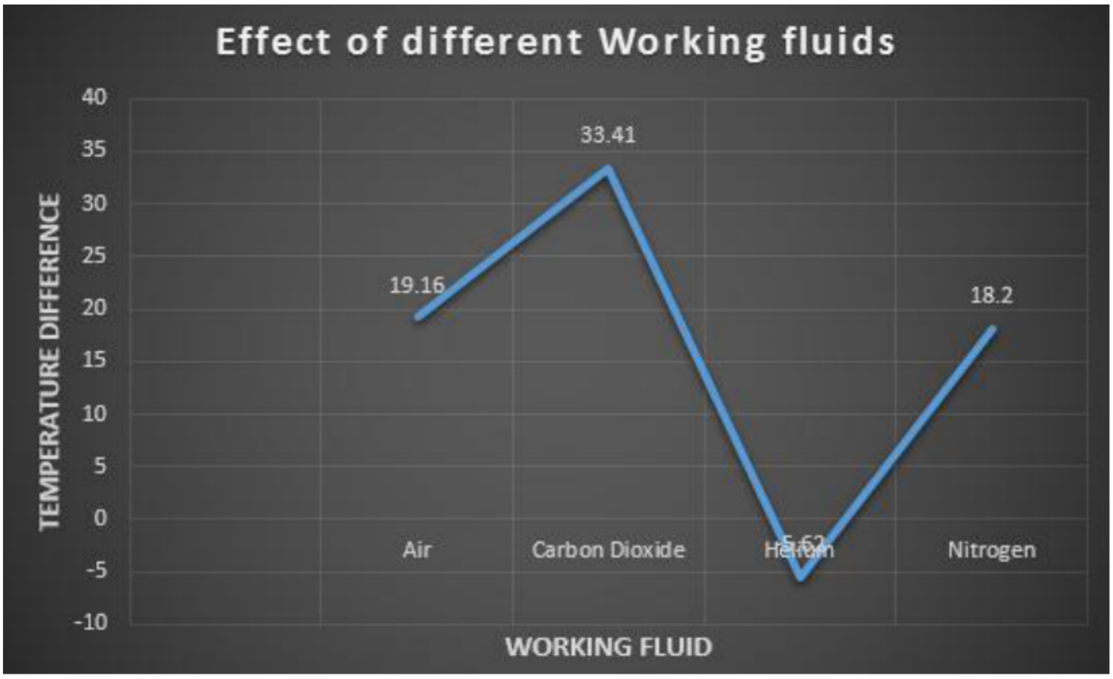
2.6. Working Fluid

Choice of the working fluid which fills the resonator will depend on the resonant frequency, viscous penetration depth and thermal penetration depth. The most desirable characteristics of the working fluid is high ratio of specific heat and small Prandtl number. Prandtl number is the square of the ratio of viscous penetration depth to the thermal penetration depth and hence smaller the Prandtl number lesser is the viscous penetration compared to the thermal penetration. Several experiments conducted by scientists reveal that design applications should be kept in mind when selecting a working fluid. For example if small temperature difference is the design goal then mixtures including polyatomic gases with small specific heat ratios may be desired. The working fluid density should also be kept in mind since more the working fluid density lesser is the cooling power of the system and hence there’s a trade of between efficiency and cooling power.

3. EFFECT OF VARIATION OF PARAMETERS

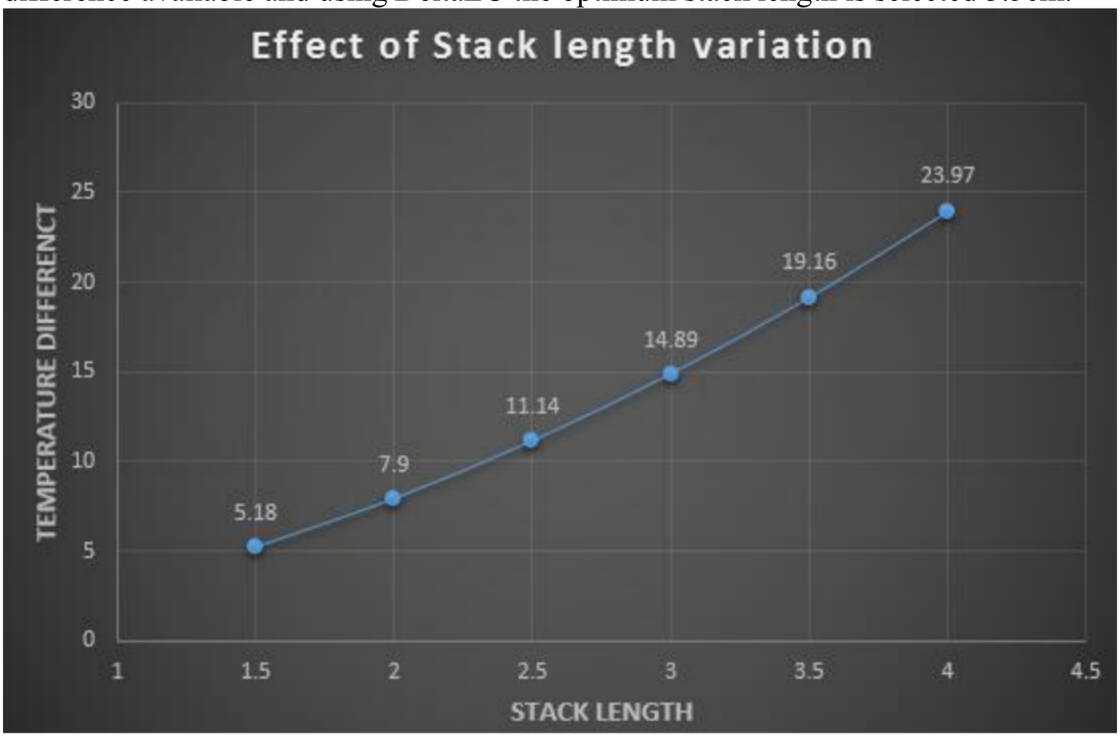
In order to select an optimum design to produce maximum temperature difference available across the stack, the design parameters involved in a piezoelectrically driven thermoacoustic refrigerator have been varied and analysed under different conditions using DeltaEC software to pin point the condition under which temperature difference is maximum. The graphs have also been plotted for the same.

The figure below shows a graph of the temperature difference (in Kelvin) across the stack versus different working fluids. It is clear from the graph that Carbon dioxide is the best choice of working fluid provided other design conditions remain the same.



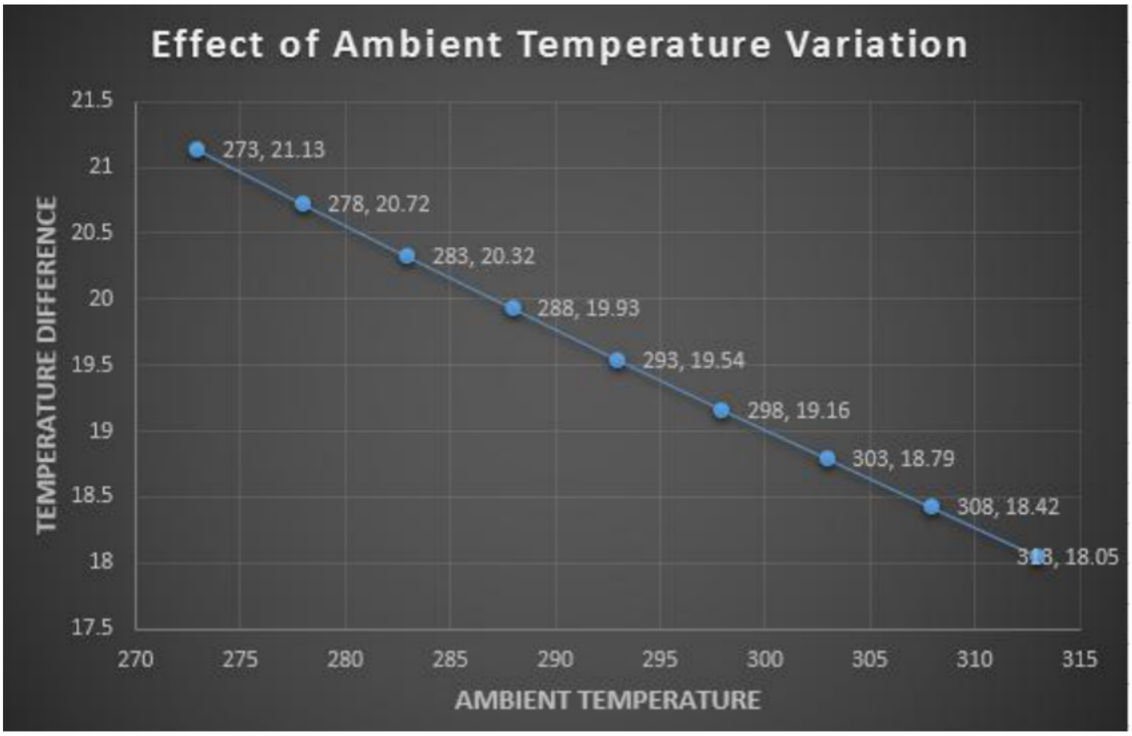
Graph 1 Effect of different working fluid on temperature difference across the stack

The figure below shows the graph of the temperature difference available across the stack (in Kelvin) versus the stack length (in cm). It is visible that as the stack length increases the temperature difference available increases, so to have maximum temperature difference the stack length should be kept maximum but we need to keep in mind that farther the cross section away from the optimum point lesser the efficiency. So a trade of is made between the efficiency and the temperature difference available and using DeltaEC the optimum stack length is selected 3.5cm.

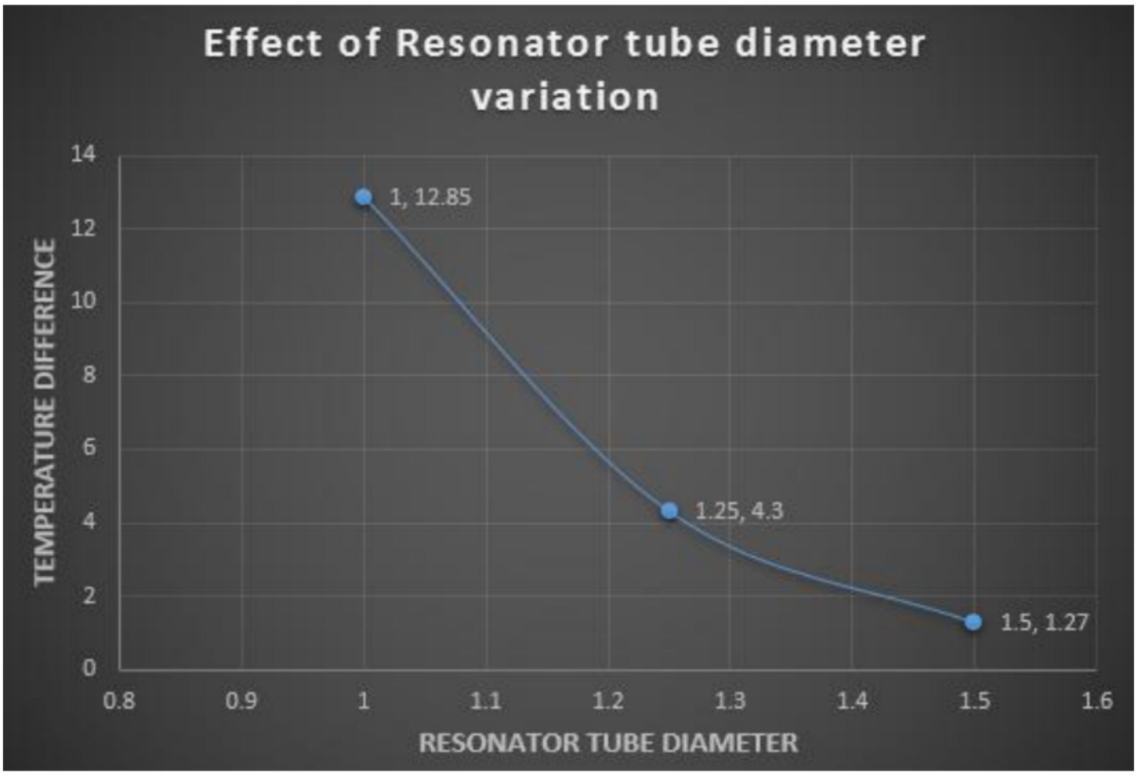


Graph 2 Effect of stack length variation on temperature difference across the stack

The following figure shows the plot of temperature difference available across the stack (in Kelvin) against the ambient temperature (in Kelvin). From the graph it is clear that the temperature difference is more where ambient temperature is less and vice versa. In the analysis of other design parameters an average value of temperature is taken which is 300K.



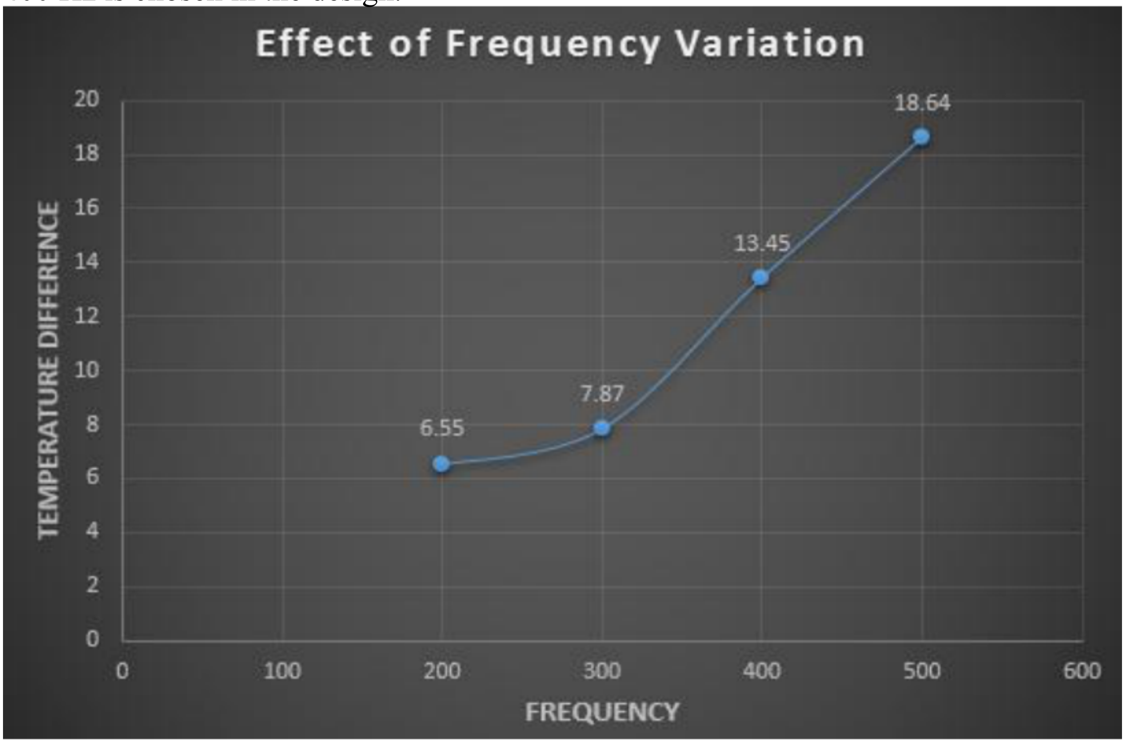
Graph 3 Effect of ambient temperature variation on temperature difference across the stack



Graph 4 Effect of resonator tube diameter variation on temperature difference across the stack

The figure above shows the graph of temperature difference available across the stack (in Kelvin) versus the resonator tube diameter (in inch). It is visible from the plot that as the tube diameter increases the temperature difference decreases. So a standard value of 1 inch is chosen in the design.

The following figure shows the graph of temperature difference available across the stack (in Kelvin) versus the frequency (in Hz). Note that with change in frequency the resonator tube length has also been changed in the analysis using the formula $\frac{\text{veocity}}{4*\text{frequency}}$ = L, where L is the resonator tube length. It is visible from the figure that with increase in frequency the temperature difference increases but the resonator tube length reduces so we can't have a very high frequency and hence an optimum value of 400 Hz is chosen in the design.



Graph 5 Effect of frequency variation on temperature difference across the stack

4. CONCLUSION

From the above discussion it is clear that to optimize the temperature difference available at the stack (which in turn is used to produce cooling effect) various design parameters need to be analysed. On varying certain parameters we found the relation between a particular parameter and the temperature difference available and have tried to maximize it. Hence, choosing the working fluid as Carbon dioxide, stack length equal to 4 cm, ambient room temperature equal to 300 K, resonator tube diameter equal to 0.875 inch and frequency equal to 400 Hz, an optimum design of a piezoelectrically thermoacoustic refrigerator which produces a temperature difference equal to 40.39 K is obtained using the DeltaEC software.

REFERENCES

[1] J. Wheatley, T. Hofler, G. W. Swift, and A. Migliori, Understanding some simple phenomena in thermoacoustics with applications to acoustical heat engines, Am. J. Phys. 53 (2), February 1985

[2] M. E. H. Tijani, Loudspeaker-driven thermo-acoustic refrigeration, Ph.D. Thesis at Technische Universiteit Eindhoven, 2001

[3] P. Merkli and H. Thomann, Thermoacoustic effects in a resonant tube, J. Fluid Mech. **70**, 161 (1975)

[4] T. J. Hofler, Thermoacoustic refrigerator design and performance, Ph.D. dissertation, Physics Department, University of California at San Diego, (1986)

[5] M. E. H. Tijani, J. C. H. Zeegers, and A. T. A. M. de Waele, Design of thermoacoustic refrigerators, Cryogenics **42**, 49-57 (2002)

[6] M. Wetzel and C. Herman, Design optimization of thermoacoustic refrigerators, Intl J. Refrig, **20**, 3-21 (1997)

[7] W. Ward, J. Clark, and G. Swift, Design Environment for Low-amplitude Thermoacoustic Energy Conversion (DELTAEC), Los Alamos NationalLaboratory: http://www.lanl.gov/thermoacoustics/DeltaEC.html

[8] Tanaji Balawant Shinde, Shailendra V. Dhanal and Shirish S. Mane. Experimental Investigation of Waste Heat Recovery System for Domestic Refrigerator. *International journal of thermal engineering*, 5(8), 2014, pp. 73–83.

[9] Ajeet Kumar Rai, Amit Kumar, Pravin Kumar and Ayaj Ahamad Ansari. Experimental Study on A Domestic Refrigerator Using Lpg As A Refrigarant. *International journal of thermal engineering*, 6(11), 2015, pp. 43–49.

[10] Peethambaran K M, Asok Kumar N and John T D Adsorption Refrigeration System for Automobiles an Experimental Approach. *International journal of thermal engineering*, 5(2), 2014, pp 122–132.

[11] J. R. Belcher, W. V. Slaton, R Raset, H. E. Bass, and J. Lightfoot, Working gases in thermoacoustic engines, J. Acoust. Soc. Am. **105** (5), May (1999)