Design, Fabrication and Analysis of Thermo-Acoustic Refrigeration System

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ABSTRACT

Thermo-acoustic refrigeration is an environmental friendly technology. Its biggest advantages are that they do not use harmful gas as a refrigerant. For the safety of the environment, it is necessary to avoid the use of environmentally hazardous refrigeration by developing new alternative refrigeration technologies such as Thermo-acoustic Refrigeration System. The main aim of this work is to design and construct a small thermo acoustic refrigerator from inexpensive and readily available parts and analyzed the results. The design includes dimension of stack, selection of acoustic driver, and acoustic resonator. The experiments showed that while thermo acoustic cooling was possible, high efficiency was beyond our reach due to materials restrictions. We obtained the temperature difference of 12^0-13^0 C across stacks for constructing this simple device. Experiments show the performance can improve by using better materials such as high heat carrying capacity materials stack. Further research and development is needed in order to explore the full potential of the device in refrigeration applications.

Keyword : - *Refrigerant, Stacks .*

1. Introduction

Recent developments in the field of thermo acoustics promise to revolutionize the way that many machines currently operated. 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, or space heaters and coolers. The thermo-acoustic devices contain no adverse chemicals or environmentally unsafe elements that are characteristics of the current refrigeration systems. Thermo-acoustics deals with the conversion of heat energy to sound energy and vice versa. There are two types of thermo-acoustic devices: thermo-acoustic engine (prime mover) and thermo-acoustic refrigerator. In a thermo-acoustic engine, heat energy 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. ln 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. The efficiency of the thermo acoustic devices is currently lower than that of their conventional counterparts, which needs to be improved to make them competitive.

2. Thermo-acoustic refrigerator

A schematic illustration of the thermo-acoustic refrigerators shown in Fig. 1. It consists of an acoustic driver placed in a housing, a air -filled resonator in which a stack are placed, and a vacuum vessel in which the resonator is contained. The system is made out of separate components so that specific parts can be exchanged. In the following the design and construction of the different parts will be described in detail.

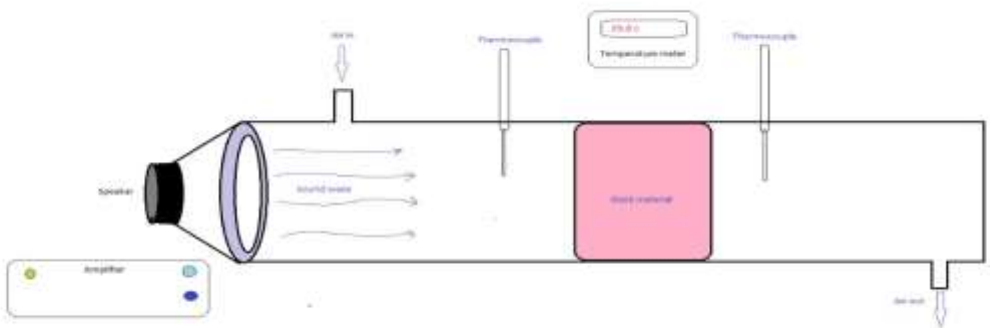


Fig -1: Thermo-acoustic refrigeration system.

2.1 Acoustic Driver

The total acoustic power used by the refrigerator is provided by an acoustic driver (speaker). A significant portion of this power is used to pump heat in the stack and the rest is dissipated in different part of the refrigerator. A higher performance of the driver leads to a higher performance of the whole refrigerator system. The acoustic driver converts electric power input to the acoustic power. The most common loudspeaker is of electro dynamic type which uses copper wires and permanent magnet. A Loudspeaker with the maximum power of 15W was selected as the acoustic driver for this project.

Acoustic driver attached to one end of the resonator, in order to create an acoustic driver attached to one end of the resonator, in order to create an acoustic standing wave in the gas at the fundamental resonant frequency of the resonator. The acoustic driver converts electric power to the acoustic power. In this study, a loudspeaker with the maximum power of 15 W, and impedance of 8Ω at the operating frequency (350 Hz, 450 Hz, 550 Hz) is used as the acoustic driver (G 50 FFL, VISATON). The loudspeaker is 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 the pressure inside the resonator is high. Consequently, the range of pressure amplitudes inside the resonator is limited.

2.2 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. The length of resonator tube corresponding to half the wave length of the standing wave.

As discussed earlier an acoustic driver with the resonance frequency of 350 Hz was selected for the present design. For this resonance frequency the length of the resonant tube was equal to 671.59 mm that corresponds to the half wavelength of the acoustic standing wave, the diameter of the resonator tube was set equal to 103.32 mm to accommodate the size of the acoustic driver.

2.3. Stack

The most important components of a thermo acoustic device is the stack inside which the thermo acoustic phenomenon occurs. Thus the characteristics of the stack have a significant impact on the performance of the thermo acoustic device. The stack material should have good heat capacity but low thermal conductivity. The low thermal conductivity for the stack material is necessary to obtain high temperature gradient across the stack and heat capacity larger than the heat capacity of air. In addition the stack material should minimize the effects of viscous dissipation of acoustic power.

There are different geometrical configurations of stack such as; parallel plates, circular, hexagonal and square pin arrays. These geometries are used to have efficient thermal contact between the working fluid and the solid surface across the cross sectional area. The pin array and parallel plates stack have shown to be the best geometries. Numerical studies confirm that efficiency and power are almost 10% to 20% more with parallel sided channel than honeycomb channel. The best location to put stack inside the resonator is about λ/20 from the nearest velocity node. In this project, aluminum foil is used as the stack and is placed 45 mm from the speaker end.

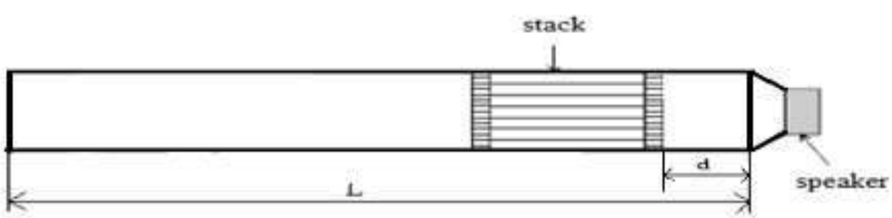


Fig -2: Stack position

There are three main stack design parameters which are normalized stack position (X_n), normalized stack length (L_n), and the stack cross sectional area *(a)*. Typically, the resonator tube cross sectional area is equal to the stack cross sectional area. The dimensionless parameters, X_n and L_n are defined as,

$$X_n = \frac{2 \times \pi \times f}{a} \times X_s$$

$$L_n = \frac{2 \times \pi \times f}{a} \times L_s$$

Where, Ls is the length of the stack and Xs is the distance from the mid length of stack to the nearest end of the resonator tube. Some other normalized parameters used in the design of the stack are,

$$\Delta T_{mn} = \frac{\Delta T_m}{T_m}$$

$$\delta K_n = \frac{\delta k}{y^0}$$

Where ΔT_m is temperature difference across the two ends of stack, T_m is the mean air temperature inside the resonator tube, ΔT_{mn} is the normalized temperature difference, δk is the thermal penetration depth, and y^0 is the half of the spacing length between the stack layers, and δK_n is the normalized thermal penetration depth.

<u>Different Types Of Stack</u>

Fig- 3 : Stainless Steel

Fig-4 : Honey Comb

Fig-5 : Wood Wool

Fig- 6 : Scrub Pad

2.4. Working Fluid

Many parameters such as power, efficiency etc. are involved in the selection of the working fluid, and it depends on the application and objective of the device. Thermo-acoustic power increases with an increasing the mean pressure inside the resonator. It also increases with an increase in the velocity of sound in the working fluid. The lighter gases such as H_2, He, Ne have the higher sound velocity. Lighter gases are necessary for the refrigeration application because heavier gases condense or freeze at low temperatures, or exhibit non ideal behavior. Air at atmospheric pressure is chosen as a working fluid for the present study.

2.5. Electronics Device

An amplifier (MPA-25, Realistic) with the maximum power output of 20 watts is used to amplify the power input to the loudspeaker to increase power input.

2.6. Thermocouple

J-type thermocouples are used for the temperature measurements in this study. They are used to measure the temperature at different locations inside the resonator and the temperature of heat exchanger fluids.

2.7. Temperature Indicator

K-type temperature indicator is used having range of 0-1200°C50 Hz, 200-240V temperature indicator.

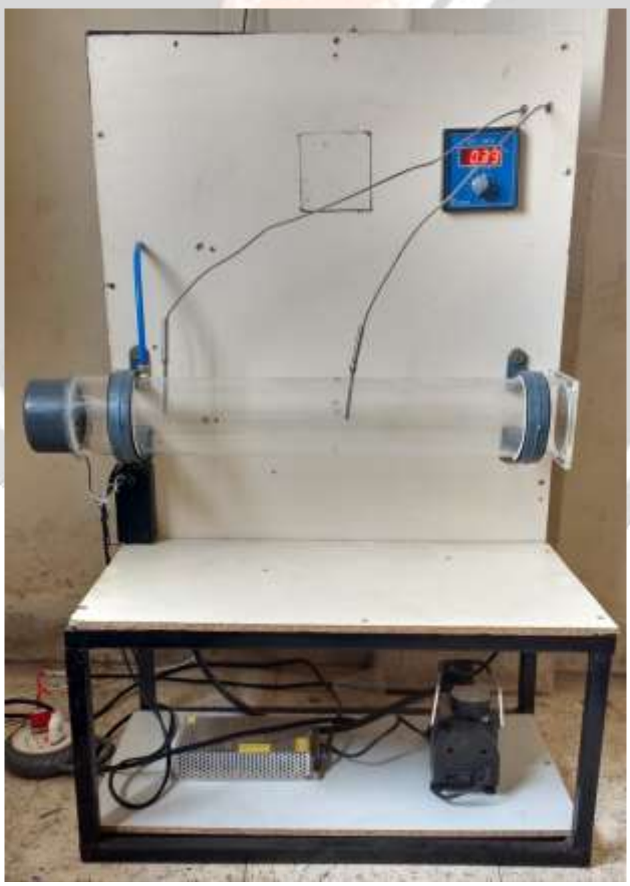


Figure - 7 : Fabricated model

3. DESIGN PROCEDURE

A total of 5 basic components have to be designed of which stack is the most important. It is not only the most critical component when it comes to the functioning of the thermo acoustic refrigerator, but also has a determining effect on the design and dimensioning of all remaining components. In order to begin with the design of the stack, first the values of all parameters are obtained and finalized. Sometimes direct values are not available. Values at particular temperatures are accurately available and using appropriate formulae, the values at operating temperatures can be calculated. The temperature gradient ΔT is indicative of the range of temperatures within which the system is going to be operating. Given the lowest temperature T_2 and the highest T_1 one can obtain the operating temperature range which is nothing but ΔT_M.

$$\Delta T_M = T_1 - T_2$$

Assuming that the maximum operating temperature is 45℃; and minimum -15℃, a temperature difference of 60 ℃ was obtained. In an effort to simplify calculations a concentrated effort has been put into converting all parameters into dimensionless form so that computations are simpler. This is achieved by normalizing them. Hence ΔT is converted into ΔT_{MN}, the normalized mean temperature difference by dividing with mean temperature T_M. Assuming mean temperature to be 300 K, a value of 0.2 is obtained.

$$\Delta T_{mn} = \frac{\Delta T_m}{T_m}$$

4. Speed of sound / Velocity of sound

$$V = a = \sqrt{\frac{c \times \gamma \times V}{V^{\gamma} \times n \times M}} \qquad \text{------- (1)}$$

Where,

V= a = velocity of sound

c = constant

Due to polytrophic or adiabatic process

$$PV^{\gamma} = C$$

$$P = \frac{C}{V^{\gamma}}$$

Put in equation (1),

$$a = \sqrt{\frac{P \times \gamma \times V}{n \times M}} \qquad \text{-------(2)}$$

From ideal gas equation,

$$P \times V = n \times R \times T$$

$$RT = \frac{PV}{n}$$

Put in equation (2),

$$a = \sqrt{\frac{R \times T \times \gamma}{M}}$$

It can be written as,

$$a^2 = \frac{\gamma \times R_{gas} \times T}{M}$$

Where,

R = 8.314 J/kg-k

M = 0.004002602 kg/mol

$$f = \frac{a}{4 \times L_R}$$

$$L_R = \frac{\lambda}{4}$$

$$d_R = \frac{\lambda}{20}$$

Resonator length, $L_R = \frac{\lambda}{4}$

Stack center position, $X_s = \frac{L_R}{2} = \frac{\lambda}{8}$ (From speaker)

$$(D_i)_R = (D_o)_S$$

$$\frac{L_R}{d_S} = 6.5$$

$$\eta(carnot\ efficiency) = 1 - \frac{T_c}{T_H}$$

$$(COP) = \frac{T_c}{T_H - T_c}$$

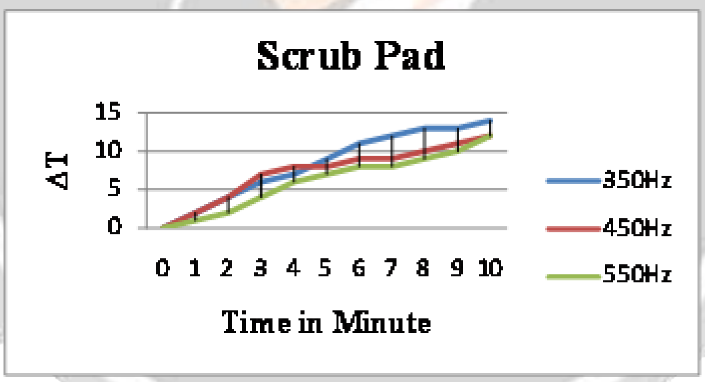
$$\delta_K = \sqrt{\frac{K}{\pi \times f \times \rho \times c_p}}$$

$$\delta_v = \sqrt{\frac{\mu}{\rho \times \pi \times f}}$$

5. RESULT

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 of stack, 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. The position of the stack is important in order to get maximum temperature gradient across the stack.
2. 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.
3. The best stack material is found to be honey comb material which gives the maximum temperature difference.



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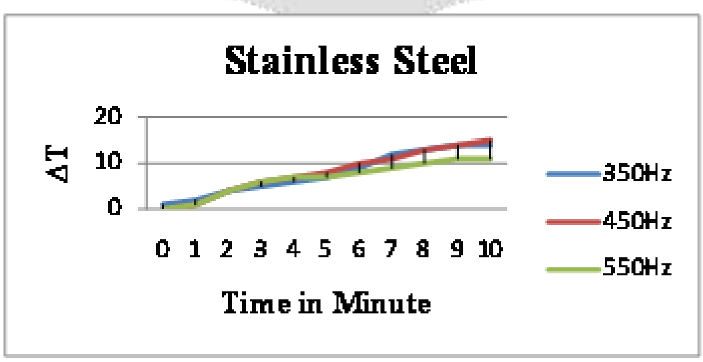

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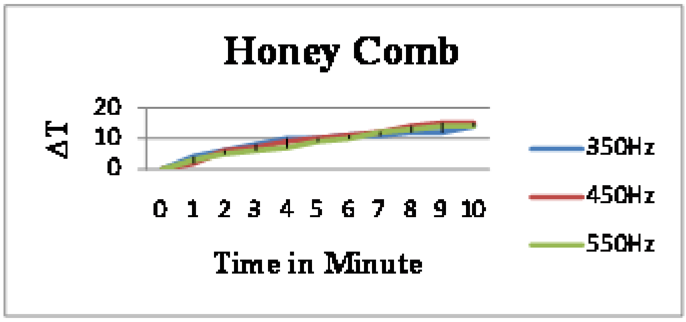

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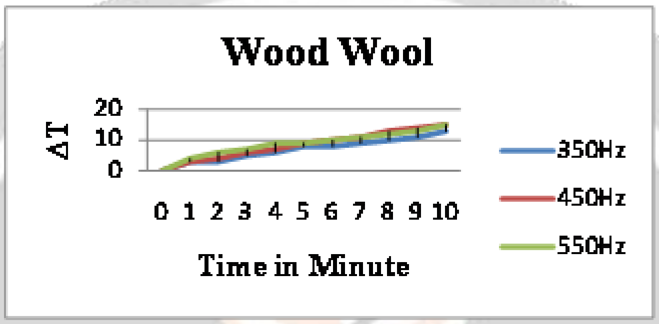

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6. CONCLUSION

We set out upon this project with the simple goal of constructing a cheap, demonstrative model of a thermo-acoustic refrigerator. To this end we succeeded: this experiment proved that thermo-acoustic refrigerators indeed work. Additionally, this experiment did yield some discoveries regarding the efficiency of thermo-acoustic refrigeration. It was revealed that finding the optimal frequency is essential for the maximization of efficiency. This optimal frequency was found using trial-and-error, because the equation used to calculate frequency was ineffective. Another factor that increased efficiency was the proper sealing of the apparatus. If the parts are not properly sealed, heat escapes from the refrigerator, and it does not function as well. However, the overall efficiency of such an apparatus is debatable. Our research shows that thermo-acoustic refrigeration has the potential to replace conventional refrigeration.

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