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Design, Development and Manufacturing of Thermoacoustic Cooler

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***Abstract*—This paper describes design, development and manufacturing of Thermoacoustic cooler. Refrigeration system is the basic need for preservation of food, human comfort, maintaining temperature for measuring tools etc. The general refrigeration system uses refrigerants as CFCs, HFCs, ammonia, R134a, R11, R22, R717 etc. As these refrigerants are harmful and are the reason for depletion of ozone layer which causes skin cancer, eye damage, global warming etc. So, to eliminate this problem the thermoacoustic refrigeration are designed.**

Thermo acoustic have been known for over years but the use of this phenomenon to develop engines and pumps is fairly recent. Thermo acoustic refrigeration is one such phenomenon that uses high intensity sound waves in a pressurized gas tube to pump heat from one place to other to produce refrigeration effect. In this type of refrigeration all sorts of conventional refrigerants are eliminated and sound waves take their place. All we need is a loud speaker and an acoustically insulated tube. Also this system completely eliminates the need for lubricants and results in 40% less energy consumption.

INTRODUCTION

A. Basic Refrigeration Principles

Gases get hotter when you compress them into less volume because you have to work to push their energetic molecules together. When you expand a gas, it is suddenly able to occupy much more volume. The heat energy its molecules contain is now divided over a much bigger volume of space, so the temperature of the gas falls . The other principle at work in a refrigerator is that when you have two things that are different temperatures that touch or are near each other, the hotter surface cools and the colder surface warms up. This is called the Second Law of Thermodynamics. Using the same principle, refrigeration works by removing heat from a product and transferring that heat to the outside air.

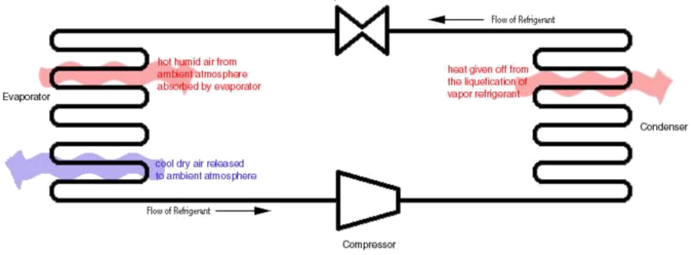

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Figure 1. Schematic diagram of Refrigeration System

Refrigeration is a process of removing heat from a low-temperature reservoir and transferring it to a high-temperature reservoir. The work of heat transfer is traditionally driven by mechanical means

There are five basic components of refrigeration system:-

- Evaporator
- Compressor
- Condenser
- Expansion Valve
- Refrigerant

To conduct the heat from the product in order for the refrigeration cycle to operate successfully each component must be present within the refrigeration system.

The Evaporator

The purpose of the evaporator is to remove unwanted heat from the product, via the liquid refrigerant. The liquid refrigerant contained within the evaporator is boiling at a low-pressure. The level of this pressure is determined by two factors: - The rate at which the heat is absorbed from the product to the liquid refrigerant in the evaporator - The rate at which the low-pressure vapor is removed from the evaporator by the compressor To enable the transfer of heat, the temperature of the liquid refrigerant must be lower than the temperature of the product being cooled. Once transferred, the liquid refrigerant is drawn from the evaporator by the compressor via the suction line. When leaving the evaporator coil the liquid refrigerant is in vapor form.

The Compressor

The purpose of the compressor is to draw the low-temperature, low-pressure vapor from the evaporator via the suction line. Once drawn, the vapor is compressed. When vapor is compressed it rises in temperature. Therefore, the compressor transforms the vapor from a low-temperature vapor to a high-temperature vapor, in turn increasing the pressure. The vapor is then released from the compressor in to the discharge line.

The Condenser

The purpose of the condenser is to extract heat from the refrigerant to the outside air. The condenser is usually installed on the reinforced roof of the building, which enables the transfer of heat. Fans mounted above the condenser unit are used to draw air through the condenser coils. The temperature of the high-pressure vapor determines the temperature at which the condensation begins. As heat has to flow from the condenser to the air, the condensation temperature must be higher than that of the air; usually between -12°C and -1°C. The high-pressure vapor within the condenser is then cooled to the point where it becomes a liquid refrigerant once more, whilst retaining some heat. The liquid refrigerant then flows from the condenser in to the liquid line.

The Expansion Valve

Within the refrigeration system, the expansion valve is located at the end of the liquid line, before the evaporator. The high-pressure liquid reaches the expansion valve, having come from the condenser. The valve then reduces the pressure of the refrigerant as it passes through the orifice, which is located inside the valve. On reducing the pressure, the temperature of the refrigerant also decreases to a level below the surrounding air. This low-pressure, low-temperature liquid is then pumped in to the evaporator.

B. Introduction to Thermo Acoustic Cooling

1. What is thermoacoustic cooler?

- Sound can be used to generate temperature differences that allow the transport of heat from a low temperature reservoir to an ambient at higher temperature, resulting in a thermoacoustic cooling system.
- Thermoacoustic cooler is the interaction between heat and sound. TAR is a refrigerator that uses sound waves in order to provide the cooling effect.
- Working medium used are inert gas.
- Compressor is replaced by a loudspeaker.

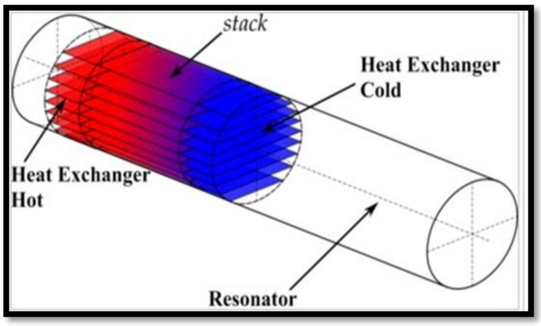

Figure 2. Basic diagram of thermo-acoustic cooler.

Thermo-acoustic device basically consists of heat exchangers, a resonator, and a stack (on standing wave devices) or regenerator (on travelling wave devices). Depending on the type of engine a driver or loudspeaker might be used as well to generate sound waves.

- **Heat exchanger:** There are basically two heat exchangers namely hot heat exchanger and cold heat exchanger. They located at the start (hot heat exchanger) and end point (cold heat exchanger) of the stack.
- **Resonator tube:** It is a long tube made of leakage proof, non-conducting material. In this part we achieve the lower temperature of the gas. This the part of refrigerator which is only there for maintaining the acoustic wave. Because it is a dead volume which causes heat loss and adds bulk, quarter wavelength resonators are preferred over half wavelength. They are made of fabric tubes.
- **Stack:** These are parallel plates separated by 3 to 4mm gaps, which are placed in the tube. These stacks reduce the area of cross section and causes the refrigeration effect. They are made of Aluminum, paper etc.
- **Acoustic driver:** The loudspeakers are used to causes sound of specific frequencies. This will help the inner gas molecules to impose energy on adjacent gas molecules by collision and thus will help in causing temperature difference. The loudspeaker and stack are kept away from each other by maintaining so distance.
- **Medium:** The medium used in this system is mostly inert gases like helium, argon. Alternatives like air, nitrogen can also be used.

2. Types of thermoacoustic coolers:

There are basically two types of TAR namely

- **Standing wave TAR:** The standing wave TAR uses a fixed number of oscillations with nodes that remain unchanged over time. In other words, the wave of as a whole does not move over time, remaining stationary. This is similar to a situation where you take a string and fixed two ends and then pluck it. Because of the fixed ends the wave of the string remains fixed in place.
- **Travelling wave TAR:** The traveling wave TAR, as it sounds like, makes use of a wave of sound that travels across the TAR. This is analogous to the situation where you take the string and flick it forward like a whip. The disturbance of the whip creates a sound wave that sends the wave forward.

LITERATURE REVIEW

1. **M.E.H. Tijani, J.C.H. Zeegers, A.T.A.M. de Waele, 'Construction and performance of a thermo-acoustic refrigerator', by Department of Applied Physics, Eindhoven University of Technology, Netherlands, December 2001.**
The construction of the different parts of the refrigerator is described in detail. The system has been assembled and the first performance measurements have been done. The measurements show that the system behaves very well as expected. A low temperature of -65˚C is achieved. The refrigerator is used to study the effect of some important thermoacoustic parameters, such as the Prandtl number using binary gas mixtures, and the stack plate spacing. This paper deals with the construction and performance of a thermoacoustic refrigerator. The manufacturing of the different components of the apparatus will be explained along with the reasons for using specific materials. The setup consists of three major parts: The refrigerator which is contained in a vacuum vessel, the electronic apparatus necessary for the measurements and acquisition of the experimental data, and the gas-control panel which is used to fill and purge the system and to prepare gas mixtures.

2. **'Design of thermo-acoustic refrigerators', by M.E.H. Tijani, J.C.H. Zeegers, A.T.A.M. de Waele, Department of Applied Physics, Eindhoven**

University of Technology, Netherlands, December 2001.

In this paper the design of thermoacoustic refrigerators, using the linear thermoacoustic theory, is described. Due to the large number of parameters, a choice of some parameters along with dimensionless independent variables will be introduced. The design strategy described in this paper is a guide for the design and development of thermoacoustic coolers. The design procedure of a thermoacoustic refrigerator has been discussed. They began the design by using the approximate short-stack and boundary-layer expressions for acoustic power and heat flow. It was shown how the great number of parameters can be reduced using dimensionless parameters and making choices of some parameters. The optimization of the different parts of the thermoacoustic refrigerator has been discussed.

3. **Design Guidelines for a Thermoacoustic Refrigerator by Ram C. Dhuley, M.D. Atrey Department of Mechanical Engineering Indian Institute of Technology Bombay, Powai, Mumbai.**
In this research paper main focus is on the design of the stack using the different parameters. A simple design procedure for a standing wave thermoacoustic refrigerator has been described. With a choice of operating parameters and helium as working gas, graphical approach has been used to determine the geometrical parameters of the stack. A refrigerator producing a cooling power of 4W at cold end temperature of 210K at steady state is designed theoretically using this design procedure.

4. **'The optimal stack spacing for thermo-acoustic refrigeration', M.E.H. Tijani, J.C.H. Zeegers, A.T.A.M. de Waele, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, Netherlands, 2002.**
In this research paper design od stacks is given. Stack is heart of thermoacoustic Refrigerator and hence its design is very important part of this experiment. It also investigates the effects of operating conditions on the performance of a thermoacoustic refrigerator. The performance of a thermoacoustic refrigerator is evaluated based on the heating load, frequency and coefficient of performance (COP). The operating conditions investigated are acoustic power, stack geometry and pressure.

5. **'Study on A Standing Wave Thermoacoustic Refrigerator using readily available materials', Jinshah B S, Ajith Krishnan R, Sandeep V S, International journal of scientific and research publication, Volume 3, Issue 7, July 2013.**
Author 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.

DESIGN AND CALCULATIONS

A. Stack Design

Frequency:

As the power density in the thermoacoustic devices is a linear function of the acoustic resonance frequency an obvious choice is thus a high resonance frequency. On the other hand, δk is inversely proportional to the square root of the frequency which again implies a stack with very small plate spacing. Making a compromise between these two effects and the fact that the driver resonance has to be matched to the resonator resonance for high efficiency of the driver, we choose to use a frequency of 400 Hz. [1]

Average pressure (Pm):

Since the power density in a thermoacoustic device is proportional to the average pressure Pm, it is favorable to choose pm as large as possible. This is determined by the mechanical strength of the resonator. On the other hand, δk is inversely proportional to square root of Pm, so a high-pressure result in a small δk and small stack plate spacing. This makes the construction difficult. Taking into account these effects and also making the preliminary choice for helium as the working gas, the maximal pressure is 12 bar. We choose to use 10 bars. [2]

Dynamic pressure (P0):

The dynamic pressure amplitude P0 is limited by two factors namely, the maximum force of the driver and non-linearities. The acoustic Mach number is defined as [2]

$$M = \frac{\mathrm{P0}}{\mathrm{\rho m} \times a^2} \quad \dots (1)$$

Here, M≈0:1 for gases in order to avoid nonlinear effects. So the dynamic pressure obtained is,

$$\mathrm{P0} = M \times \mathrm{\rho m} \times a^2 \quad (2)$$

= 0.156 bar = 0.2 bar (approx).

Drive ratio (D):

Drive ration defined as the ratio of dynamic pressure to average pressure. For design of refrigerator of moderate cooling power drive ratio is always less than 3%. [2]

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$$D = \frac{\mathrm{P0}}{\mathrm{Pm}} \quad \ldots (3)$$

$$= \frac{0.2}{10}$$

$$= 2\%$$

Geometry of stack:

There are many geometries which the stack can have: parallel plates, circular pores, pin arrays, triangular pores, etc. The geometry of the stack is expressed in Rott's function fk . It is shown that the cooling power is proportional to Im(-fk). Fig. 2 shows the real and imaginary parts of fk for some geometries as functions of the ratio the hydraulic radius rh and the thermal penetration depth. The hydraulic radius is defined as the ratio of the cross-sectional area and the perimeter of the channel.

Pin arrays stacks are the best, but they are too difficult to manufacture. Hence, we choose to use a stack made of parallel-plates. We note that for parallel-plate stack rh = y0. Here y0 is the half stack spacing. The stack spacing for parallel plates is given by 2δk or 4δk.[2]

Thermal depth of penetration (δk):

$$\delta\mathrm{k} = \sqrt{\frac{2k}{\rho \times Cp \times \omega}} \quad \ldots (4)$$

$$= \sqrt{\frac{2 \times 0.16}{0.179 \times 10^3 \times 2512 \times 5.19}}$$

= 0.3703mm.

Stack spacing = 4 δk

$$= 4 \times 0.3703 = 1.4812.$$

Optimal stack spacing = 2 y0 = 1.4812.

$$\mathrm{y0} = 0.7406$$

Viscous depth of penetration (δ_v):

$$\delta_v = \sqrt{\frac{2 \times \mu}{\rho \times \omega}} \quad \ldots (5)$$

Here, μ is the kinematic viscosity, and

$$\mu = \frac{\sigma \times k}{cp} = 0.02096\, {}^{Ns}/_{m^2}$$

$$\delta_v = \sqrt{\frac{2 \times 0.02096}{0.179 \times 10^3 \times 2512}} = 0.305mm$$

Plate thickness of stack (2l):

The thickness of the stack plate can be calculated by the blockage ratio i.e. porosity formula.

$$Porosity\ (B) = \frac{\mathrm{y0}}{\mathrm{y0} + \mathrm{l}} \quad \ldots (6)$$

$$2l = 2 \times \mathrm{y0}\left(\frac{1}{B} - 1\right)$$

$$= 2 \times 0.7406\left(\frac{1}{0.75} - 1\right)$$

$$= 0.4937mm.$$

Half plate thickness (l) = 0.24685mm.

Stack perimeter (∏):

The stack perimeter is given by,

$$\prod = \frac{A}{\mathrm{y0} + \mathrm{l}} \quad \ldots (7)$$

Here A is the cross-sectional area of stack. Assume diameter of stack is 50mm, the we get

$$A = \frac{\pi}{4} \times 50^2 = 1962.5mm^2$$

Therefore, perimeter of stack is,

$$\prod = \frac{1962.5}{0.7406 + 0.24685} = 1987.442mm.$$

Main stack parameters:

We remain with three main stack design parameters: the center position xn, the length Lsn; and the cross-sectional area A. This area is equal to the resonator cross section at the stack location. By using data for the gas parameters, we first optimize the stack geometry parameters by optimizing the performance expressed in terms of the coefficient of performance (COP) which is the ratio of the heat pumped by the stack to the acoustic power used to accomplish the heat transfer. This leads to the determination of xn and Lsn: Then the required cooling power will be used to determine the cross-sectional area A. Once these parameters are determined we can design the resonator. [2,3]

Normalized temperature gradient (Γ),

$$\Gamma = \frac{\Delta Tmn}{(\gamma - 1) \times B \times Lsn} \times \tan(xn) \quad \ldots (8)$$

Normalized cooling power (Q_{cn}),

$$Qcn = \frac{-\delta k \times D^2 \times \sin(2xn)}{8\gamma(1+\sigma)\Lambda} \times \left[\left(\frac{\Delta Tmn \times \tan(xn)}{(\gamma-1)B \times Lsn}\right)\left(\frac{1+\sqrt{\sigma}+\sigma}{1+\sqrt{\sigma}}\right) - \left(1+\sqrt{\sigma}-\sqrt{\sigma}\times\delta kn\right)\right] \quad \ldots (9)$$

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Normalized acoustic power (Wn),

$$W = \frac{\delta kn \times Lsn \times D^2 \times (\gamma - 1)B \times (\cos xn)^2}{4\gamma} \times \left(\frac{\Delta Tmn \times \tan(xn)}{(\gamma - 1)B \times Lsn \times (1 + \sqrt{\sigma})\Lambda} - 1 \right) - \left(\frac{\delta kn \times Lsn \times D^2}{4\gamma} \right) \left(\frac{\sqrt{\sigma} \times (\sin xn)^2}{B \times \Lambda} \right)$$

… (10)

Here Λ is defined as,

$$\Lambda = 1 = \sqrt{\sigma} \times \delta\text{kn} + \frac{1}{2} \times \sigma \times (\delta\text{kn})^2$$

Coefficient of performance is given by,

$$COP = \frac{Qcn}{Wn}$$

… (11)

For different stack lengths we will get different stack center positions and so the COP will also differ. Near the acoustic driver the COP is higher.

B. Resonator:

The acoustic power lost per unit surface area is given by,

$$\frac{dW}{dS} = \frac{1}{4} \times \rho \times |<u1>|^2 \times \delta_v \times \omega + \frac{1}{4} \times \frac{|P1|^2 \times (\gamma - 1) \times \delta k \times \omega}{\rho \times a^2}$$

… (12)

Here the first term is the kinetic energy dissipated by viscous shear and the second term is the energy dissipated by thermal relaxation.

Acoustic resonator can have length of λ/2 or λ/4. As the total dissipated energy is proportional to surface area of resonator, λ/4 resonator will dissipate only half the energy dissipated by λ/2 resonator. So λ/4 resonator is preferred. [2]

Length of resonator (L) = λ/4

And, $$\lambda = \frac{a}{f} = \frac{935}{400} = 2.3375m = 2337.5mm$$

$$L = \frac{2337.5}{4} = 584.375mm$$

C. Performance of the system:

The total acoustic power is given by,

$$Wt = Ws + Wres + Wchx + Whhx$$

… (13)

The coefficient of performance for the system is,

$$COP = \frac{Qc}{Wt}$$

… (14)

. EXPERIMENTAL SETUP DIAGRAM

Picture 3. Experimental diagram

AUTOMATION OF THERMOACOUSTIC COOLER

Components used

1. Arduino Nano

The Arduino Nano is a small, complete, and breadboard friendly board based on ATmega328P. It has more or less the same functionality of Arduino Demilune, but in different packages. It lacks only a DC power jack and works with a Mini-B USB cable instead of standard one.

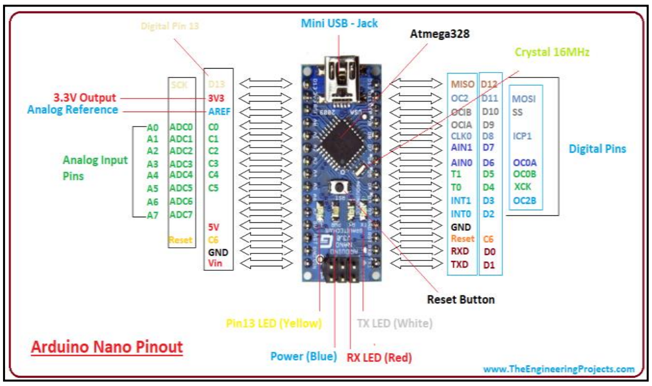

Figure 4 . Arduino Nano

Arduino Nano Pinout contains 14 digital pins, 8 analog Pins, 2 Reset Pins & 6 Power Pins. Each of these Digital & Analog Pins are assigned with multiple functions but their main function is to be configured as input or output. Arduino Nano comes with a crystal oscillator of frequency 16 MHz.

2. Relay

This is a small and easy to use 1 channel relay board that operates on 5V. Use it to control one 240V power appliance lights, fans, etc directly from microcontrollers or low voltage circuits. The relay can handle a maximum of 7A/240 V AC or 7A/24V DC. Relay has all three connections - Common (COM), Normally Open (NO), Normally Closed (NC) brought out to 3 pin screw terminals which makes it easy to make and remove connections. The board has a power indication (RED) and a relay status (GREEN) LED to ease debugging. The board can accept inputs within a wide range

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of voltages from 3V to 5V. Power input and relay control signals are brought to 3 pin header pins on the board. Hence, the board can be easily interface with our development boards using our female to female jumper wires.

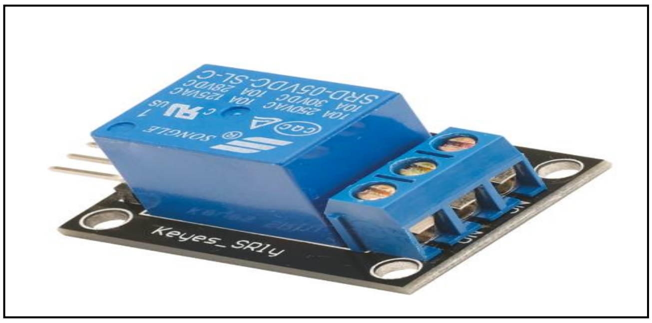

Figure 5. Relay Switch

3. MPU 6050 Model

MPU6050 sensor module is complete 6-axis Motion Tracking Device. It combines 3-axis Gyroscope, 3-axis Accelerometer and Digital Motion Processor all in small package. Also, it has additional feature of on-chip Temperature sensor. It has I2C bus interface to communicate with the microcontrollers

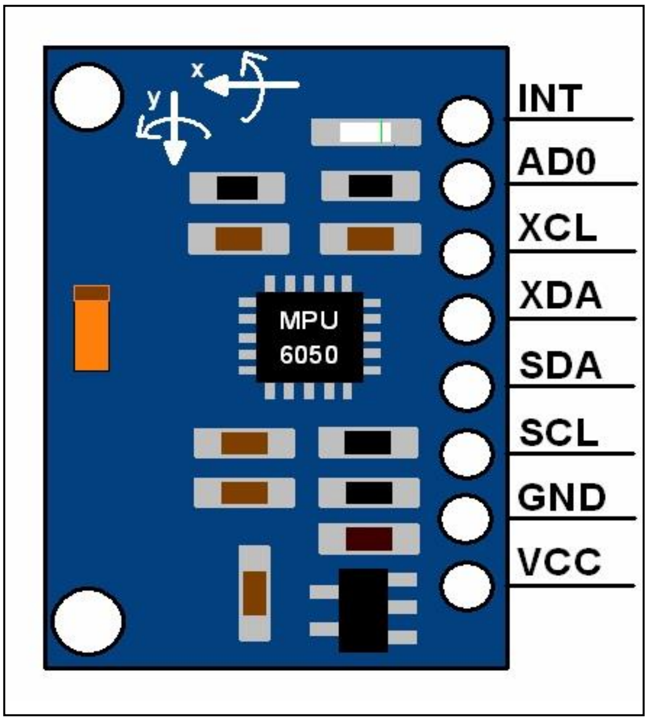

Figure 6: MPU-6050 MODEL

The MPU-6050 module has 8 pins,

INT: Interrupt digital output pin.

AD0: I2C Slave Address LSB pin. This is 0th bit in 7-bit slave address of device. If connected to VCC then it is read as logic one and slave address changes.

XCL: Auxiliary Serial Clock pin. This pin is used to connect other I2C interface enabled sensors SCL pin to MPU-6050.

XDA: Auxiliary Serial Data pin. This pin is used to connect other I2C interface enabled sensors SDA pin to MPU-6050.

SCL: Serial Clock pin. Connect this pin to microcontrollers SCL pin.

SDA: Serial Data pin. Connect this pin to microcontrollers SDA pin.

GND: Ground pin. Connect this pin to ground connection.

VCC: Power supply pin. Connect this pin to +5V DC supply.

Circuit Diagram:

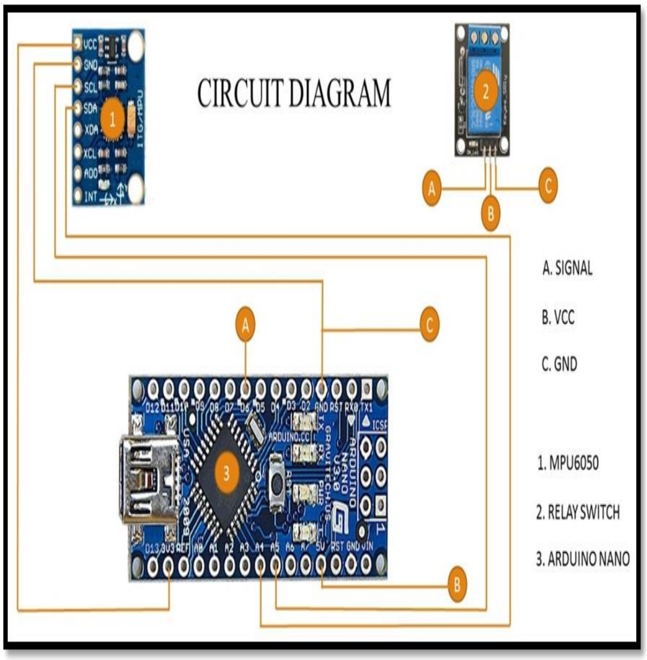

Figure 8. Circuit diagram of automation part of TAR.

A4 is Nano's SDA pin.
A5 is Nano's SCL pin.
SCL= Serial clock
SDA= Serial data
MPU6050 works on I2C communication protocol.

TESTING AND RESULTS:

Materials of stack	Stack thickness (l)	Stack spacing (y_0)	Temperature (°C) for corresponding time (in mins)			
			0	10	20	30
Aluminium sheet (parallel plates)	0.5	1.5	33.1	32.6	32.3	31.4
Aluminium sheet (parallel plates)	0.5	3	33.1	33	32.7	32.4
Gateway paper (parallel plates)	0.2	1.5	33.1	32.8	32.2	32.8
Paper straw	0.1	6	33.1	33.1	32.9	32.4
Plastic straw	0.1	8	33.1	33	33	33.3

Table 8. Combined result of stacks (50mm distance from speaker).

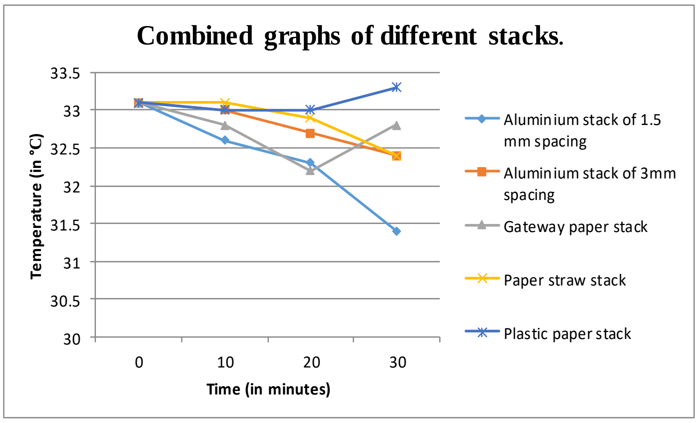

Figure 14. Combined graph of different stacks.

Results:

- The aluminium stacks of 1.5 mm gives the best results and a maximum drop of 1.7°C in 30 minutes.
- The plastic straw stacks gets the minimum drop of 0.2°C.
- The temperature drop increases as the distance of stack from the speaker decreases and as the length of the stack increases.
- The temperature drop increases as the time increases.

CONCLUSION

- Thermoacoustic cooler eliminates the use of harmful refrigerants in the system so that the environment is less harmed. This is a eco-friendly system to give the required cooling effect.
- The efficiency of the Thermoacoustic cooler is less as compared to the efficiency of the actual refrigeration system, hence the coefficient of performance is also less.
- The temperature drop which we achieve is less and is no stable.
- To achieve greater temperature drop it requires more time i.e. 1°C drop for each half hour. The system will give better results if the cabinet is sealed perfectly.
- The temperature drop is dependent on stack material, stack spacing, stack thickness, distance of stack from the speaker, stack length and the medium in the resonator.
- The Aluminium stacks with minimum spacing gives the best results.

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