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Design and Optimization of Stack Position and Stack Spacing in Thermoacoustic Refrigeration System

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ABSTRACT: -Thermoacoustic refrigerator converts high amplitude sound waves into heat transfer energy without any refrigerant or heavy metal moving parts like piston in compressor of conventional refrigeration system. Due to Montreal and Kyoto protocols more focus got shifted to environmental friendly devices like Thermoacoustic engines that are environmental friendly which does not use harmful gas or any exotic materials. In this study, the resonance of speaker box and resonator are optimized at given specifications of 325W-RMS JBL Speaker such that resonance occur below natural frequency of the dimensions which does not damage the speaker or the components in resonator. This system has resonator of quarter wavelength with ported end and frequency of speaker is optimized at 80Hz for thermoacoustic effect to occur at stack.
Various stack fabrication method and materials for stack such as PET, FRP, and Acrylic is described. The optimization of thermoacoustic stack position and stack spacing is done analytically by Delta EC software to obtain temperature difference of $\Delta T = 54^0C$. The experimental temperature difference is found to be $\Delta T = 3.2^0C$ at stack position $\lambda/20$ from the driver.

Key Words: ***Thermoacoustic Refrigerator, Coefficient of Performance, Stack Position, Delta EC, Stack Spacing***

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I. INTRODUCTION

Almost all the heat pumping devices like compressor in refrigeration system have mechanical moving parts which generates heat and friction and eventually wear out after some time of working. Conventional refrigeration compressors have working fluid as refrigerants which are harmful to ozone layer. These conventional refrigeration systems runs on primary source (electricity) and these systems are not feasible to run on secondary source like waste heat energy and solar energy. The conventional refrigeration systems are heavy in weight.

There is no mechanical moving components therefore no friction, Additional heat, wear and tear is produced. No fossil fuel is used to power TAR therefore it helps to cut down the carbon emissions into the atmosphere. Thermoacoustic Engines are pollution free. It uses no global warming gases or ozone depletion gases for pumping heat. Thermoacoustic refrigeration system have lower weight than conventional refrigeration system.

Thermoacoustic effect principle as described by Tijani [1]shows how temperature changes with changes in pressure similar to gas parcel near stack walls of thermoacoustic refrigerator. Consider a cylinder piston arrangement contain gas closed at one end and small volume of gas as gas parcel for study.In step

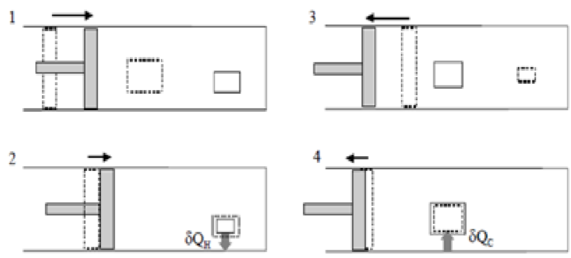

Figure 1 Piston cylinder representation of thermoacoustic effect [1]

1: Force on piston is applied which compresses the gas inside the cylinder, here displacement of gas parcel takes place. In step 2: By further increasing the force on the piston the gas parcel compresses and ejects heat onto the surrounding wall of cylinder. In step 3: While lifting the force on the piston it moves back towards left direction which also displaces gas parcel to same direction. In step

4: The gas parcel expands and is cooler than the local wall temperature, heat flows irreversibly from cylinder wall to gas parcel and cycle starts again. After many cycles right end gets warmer while left end gets cooler, this results in temperature gradient across the cylinder. This effect occurs in thermoacoustic stack walls where loudspeaker driver moves rapidly as piston and resonator resonates at peek amplitude to provide local pressure points inside the stack wall same as cylinder in this case.

In Research papers [1], [3] stack is positioned closer to Driver, which shows that when stack is closer to driver, the conversion of acoustic power to thermoacoustic effect is high. The cross sectional area of driver, resonator an stack should be same for better performance and uniform acoustic field with low distortion. From paper [2] stack length range observed should be $L\_s \ll \lambda/2\pi$.From paper [2] stack spacing should be between $2\delta_k$ to $4\delta_k$ but from paper [4] this range is shortened to $2.5\delta_k$ to $3\delta_k$. By paper [8] stack plate thickness range found was between 0.5mm to 0.15mm but in paper [7] they found optimum stack plate thickness to be 0.3mm. Therefore concluded stack plate thickness range is between 0.3mm to 0.15mm. From paper [7] stack position in resonator is kept at a distance of $\lambda/20$ from acoustic node and in paper [8] it is concluded between $\lambda/20$ to $\lambda/8$. The appropriate resonator length is quarter of the wavelength $\lambda/4$. Such that there is low acoustic power losses. For better performance helium gas is used at 10 bar pressure inside resonator [2], while using helium at atmospheric pressure the results came same as using air at atmospheric pressure [10]. Therefore many papers used air at atmospheric pressure due to its free availability and no leakage issue. In paper [6] it is shown that lower frequency of about 250 Hz gave highest temperature difference. Therefore the range of operating frequency is taken as 80 Hz to 250 Hz. In paper [9] one of the causes due to low performance was low power of the speaker, therefore high power speaker is suggested for the system. As seen in paper [9] the shape of the driver an resonator was different which cause distortion in acoustic field result in low performance of the system, for better performance of the system the resonator shape and cross sectional area is kept same as driver specifications.

II. THERMOACOUSTIC REFRIGERATION SYSTEM

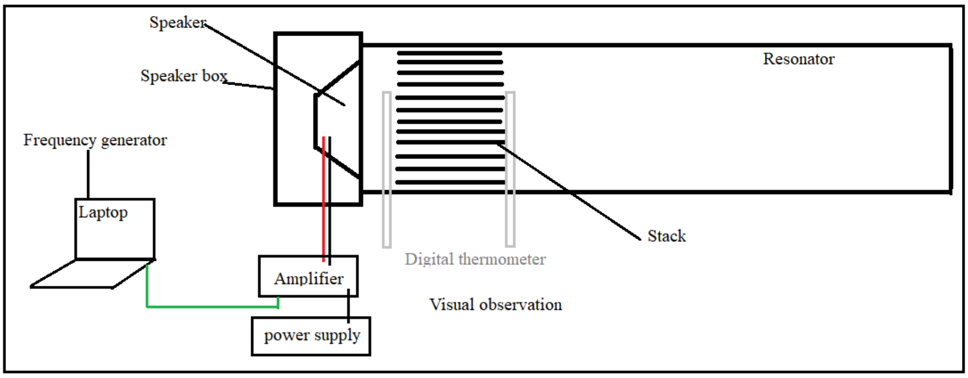

Figure 1 *Schematic diagram of Thermoacoustic refrigerator*

- First speaker box mounts speaker and resonator.
- Stack is placed inside resonator and two holes are made across the stack for digital thermometer.
- The speaker is powered by amplifier which runs on Direct current, therefore a power supply is provided to convert AC to DC.
- The frequency generator application provides various standing wave and travelling wave frequencies in a laptop which would give signal to amplifier.
- The readings are taken visually indicated on digital thermometer.

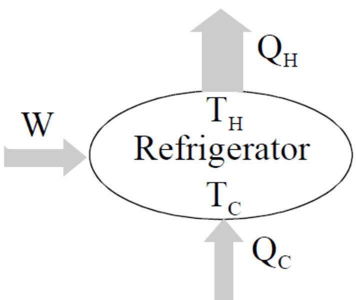

Figure 3 Thermodynamic design

- Coefficient of Performance:
  - Function of Refrigerator is to remove a Heat quantity QC at low temperature TC and to Supply a Heat Quantity QH to the surrounding at a high temperature TH. [6]
  - Considering there is no mass flow in or out of system
- By First Law of Thermodynamics
  - U = QC - QH + W
- By Second Law of Thermodynamics
  - S = (QC / TC) - (QH / TH) + Si
- Integration Over one cycle Yields
  - QH = QC + W
  - QH / TH = (QC / TC) + Si
- We know, COP = QC /W
  - COP = QC/ QH – QC
- Since Si > 0
  - (QC / TC) ≤ (QH / TH)
- This gives,
  - COP ≤ TC / (TH – TC)
- Carnot coefficient of performance (Maximum performance)
  - COP_{carnot} = TC / (TH - TC)
- This COP can be made larger than one if TC > TH/2

III. DELTA EC DESIGN SELECTION

- Design parameter range :
- Stack Length $L_s << (\lambda/2\pi)$
- Stack Position $x_s = \lambda/20$ to $\lambda/8$
- Stack plate thickness = $2y_0$ to $3.5y_0$
- Frequency Range = 30 Hz to 250 Hz
- Resonator length range = 0.1977m to 1.1125m
- In all Delta Ec models
  - the test ran at atmospheric air pressure
  - Speed of sound and air density is taken with respect to 40^0 C
  - Hot side of stack is at 40^0C

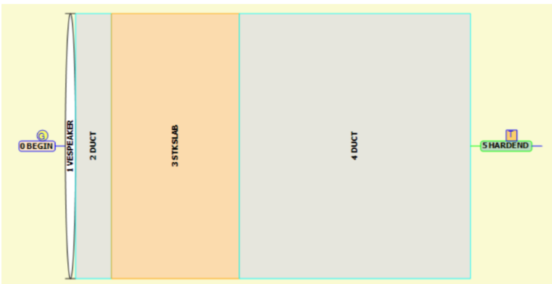

Figure 4 TAR Model MS2 Schematic diagram at λ/20 and Ls = 225mm

3.1 Delta Ec Model MS2

- Speaker manufacture recommended volume setting of speaker back box is 28.32 liters, and front box (resonator) is 35.40 liters.
- Dimensions of resonator:
  - Resonator diameter as per dimensions of Speaker = 312mm >311mm(speaker)
  - Length of resonator $L_r = \frac{V}{\pi r^2}$ = 463.024mm
  - Resonator face end surface area = 0.07645 m^2
- Frequency = $\frac{c}{4 L_r}$ =192.21 Hz
- Stack length $L_s << (\lambda/2\pi = 294.76mm)$
  - Stack length to be tested = 100mm, 150mm, 225mm(max)
- Stack position from driver = λ/20 =92.6mm
- Temperature difference obtained = 37^0C
- Conclusions of this model:
  - The temperature difference parameter got mostly changed by one specific parameter which is length of stack L_s. Showing that the increase in length of stack brings increase in temperature difference.
  - E_{dot} is the acoustic power which is affected by stack spacing $2y_0$, lower the stack spacing more the acoustic power drop occurs.
  - The acoustic power drop is lower at stack position λ/8 than at stack position λ/20. Therefore closer the stack from the driver more the acoustic power drop occurs.

The temperature difference parameter maxed only by parameter Stack length therefore in further evaluation maximum stack length is considered.

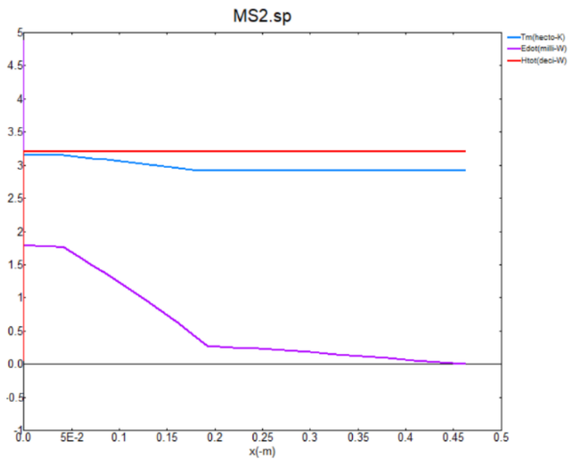

Figure 5 blue line- Temperature, red line- total power, violet line- acoustic power. At λ/20 and Ls = 225mm

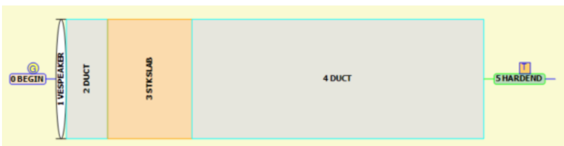

Figure 6 Schematic diagram of Delta EC Model number M 80 225

3.2Delta EC Model M 80 225

- Parameters of this model:
  - Stack length = 225mm
  - Frequency = 80Hz
  - Resonator length = 1.1125m
  - Stack position λ/20 = 222.5mm
- Temperature difference obtained = 54^0C

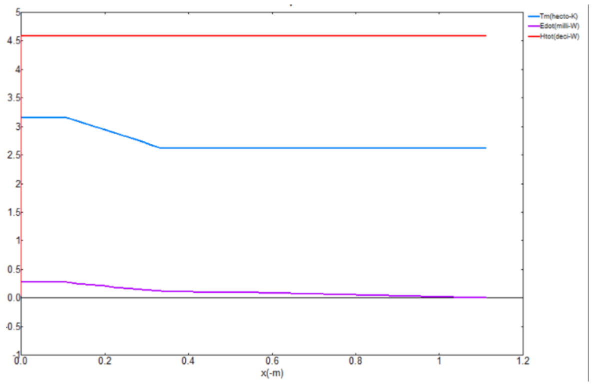

Figure 7 Delta EC model M 80 225

3.3Delta EC model M 100 225

- Temperature difference obtained = 52^0C
- The Schematic diagram is identical as previous model.
- Parameters of this model are:
  - Stack length = 225mm
  - Frequency = 100 Hz
  - Resonator length = 0.89m
  - Stack position λ/20 = 178mm

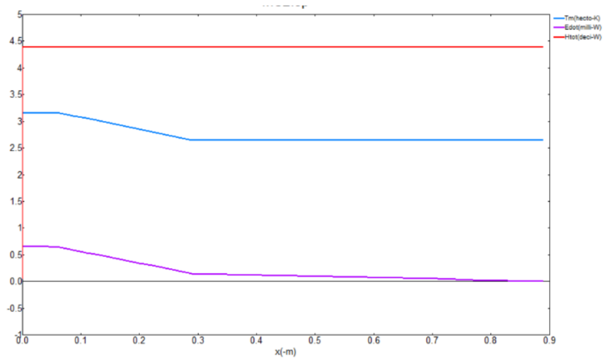

Figure 8 Delta EC model M 100 225

3.4Delta EC model M 120 225

- Temperature difference obtained = 49^0 C
- Schematic diagram is identical to model M 80 225
- Parameters of this model
  - Stack length = 225mm
  - Frequency = 120 Hz
  - Resonator length = 0.89m
  - Stack position λ/20 = 148.3mm

➢ By comparison of these four models we observe that temperature difference parameter gets higher by decrease in frequency at the cost of decrease in acoustic power.

➢ The Acoustic power in other hand increases when frequency is increased, we get more acoustic power drop in thermoacoustic stack.

➢ It is concluded that higher temperature difference results in higher cop of the system, therefore lowest frequency output of speaker 80 Hz and parameters related to it are taken into further study for optimum TAR design.

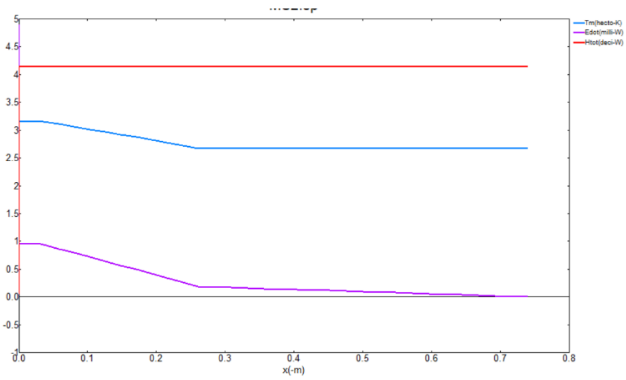

Figure 9Delta EC model M 120 225

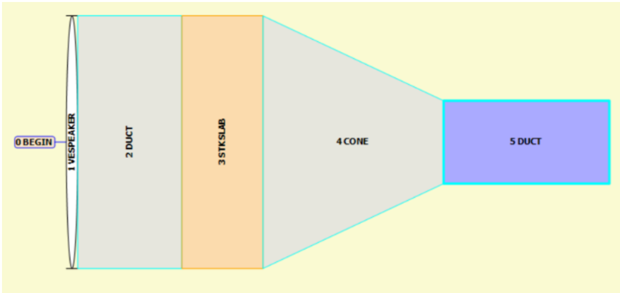

Figure 10 Schematic diagram Delta EC model M 80 225 Port 1

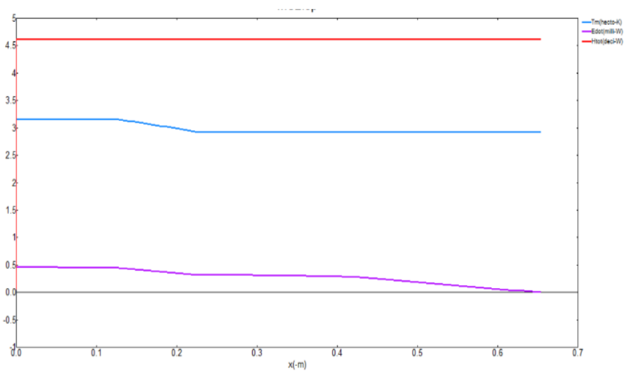

Figure 11Delta EC model M 80 225 Port 1

3.5 Delta EC model M 80 225 Port 1

- As Shown in research papers [1],[3],[4],[5] having a cone and a buffer system, modification to model M 80 225 is done by introducing cone and open end system.

Delta EC model M 80 225 Port 1

- As per speaker manufacture volume for box, resonator volume is taken as 35.4 liter.
- The volume till stack end is V_{stack} = 25612022.6 mm^3.
- Port end dimensions provided by the manufacturer are:
  - Port length = 204 mm
  - Port diameter = 102mm
  - Then port volume V_{port} = 1666941.62 mm^3
- Cone parameters
  - Cone volume $V_{cone} = V_{total} - (V_{stack} + V_{port})$= 8121035.77$mm^3$
  - Cone length = 222.25mm
  - Cone radius r_1 = 156mm
  - Cone radius r_2 = 51mm
- Parameters of this model :
  - Stack length = 225mm
  - Frequency = 80 Hz
  - Resonator length = 1.1125 m
  - Stack position λ/20 = 222.5mm
- Temperature difference obtained = 23^0 C

3.6 Delta EC conclusions

- The Model M 80 225 without combination of cone and port end gave the highest temperature difference, therefore this simple design parameters is chosen for experimental setup are given below:
  - Stack length = 225mm
  - Frequency = 80Hz
  - Resonator length = 1.1125mm
  - Resonator diameter = 312 mm
  - Stack Diameter = 310 mm
  - Stack position λ/20 = 222.5mm

Figure 12 speaker box fabrication

IV. EXPERIMENTAL SETUP

4.1Design of Speaker box

- Speaker box recommended volume by manufacturer of speaker is 28.32 liters
- Speaker dimensions in mm without wood thickness
  - = 2 X (410 X 410), 4 X (410 X 170)
- Speaker dimensions in mm with wood thickness of 12mm :
  - = 2 X (434 X 434), 2 X (434 X 170), 2 X (410 X 170)
- Speaker open face dimension:
  - Circular cut diameter for speaker: 300mm
  - Distance of perimeter of circle to the edge = 67mm
- Speaker box wood material is MDF(Medium density fiberboard)
- Speaker (driver) specifications:
  - JBL A 1500HI 1500W 12inch subwoofer
  - Diameter = 300mm
  - Frequency response = 23 Hz to 450 Hz
  - Impedance = 4 Ω
  - Motor force factor B_L = 14.08 T_M
  - Moving Mass M_{MD} = 171.00 gms
  - Maximum power output: 1500 W
  - RMS power output: 325 W

Figure 13Resonator fabrication

Figure 14 resonator and speaker box Fastening

4.2 Design of Resonator

- FRP (Fiber reinforced plastic): It is a composite material made of a polymer matrix reinforced with fibers. Polymers such as- epoxy, vinyl ester, polyester thermosetting plastic, phenol formaldehyde resins.
- Cutting dimension on FRP sheet :
  - Length of resonator = 1112.5mm + 15mm (for extruded speaker thickness)+2.5mm (cutting loss) =1127.5mm
  - Width = 986.46mm (perimeter of resonator)+15mm (for bolt and screw and fixing the circumference)+ 4mm (for cutting) = 1005 mm
  - Number of bolts = 1005/ 100mm = 10 bolts

- Fastening of speaker box and resonator:
  - Resonator fit tightly on the speaker extension and L-shaped metal couplings are used to fasten resonator on box by bolts and screws.
  - Glue is used to seal additional gaps.

Figure 15 Stack fabrication

4.3 Stack Fabrication method

4.3.1Method 1: Lamination sheets

- In this method lamination sheets of thickness 0.125mm is used to make stack.
- A lamination sheet is marked with 7 straight lines and 7 stripes of 5mm are cut and are glued on the marked lines on the lamination sheet by glue gun.
- Another sheet is glued on to the stripes by glue gun.
- The stack length is 225mm and stack diameter is 310 mm same as resonator diameter.
- To make a cylindrical stack from rectangular cuboid, each lamination sheet is cut to precise length to form a cylindrical stack when stack is fabricated.
- The table for exact lamination lengths for half of cylindrical stack, such that stack fabrication is done in two semi cylinder(150mm radius+150mm radius)
- Number of stacks = 300/5 =60 Stacks

Height of Stack(mm)	**Angle of stack from center(mm)**	**Material to cut (mm)**	**Length of sheet needed**	**Height of Stack(mm)**	**Angle of stack from center(mm**	**Material to cut (mm)**	**Length of sheet needed**
5	75.4	115.94	78.1	80	28.93	19.35	271.29
10	69.3	100.227	109.54	85	26.94	16.70	276.58
15	64.5	88.479	133.04	90	24.79	14.28	281.52
20	60.57	78.842	152.31	95	22.77	12.8	285.53
25	57	7059	168.81	100	20.78	10	289.92
30	53.07	63.34	183.30	105	18.81	8.285	293.24
35	50.7	56.89	196.21	110	16.87	6.6	296.42
40	47.89	51.07	207.84	115	14.95	5.2	299.49
45	45.2	45.79	218.4	120	13.05	4	301.99
50	42.64	40.98	228.03	125	11.159	2.9	304.13
55	40.17	36.57	236.85	130	9.28	2	305.94
60	37.79	32.52	244.94	135	7.41	1.2	307.4
65	35.49	28.80	252.38	140	5.55	0.7	308.54
70	33.25	25.38	259.22	145	3.699	0.32	309.35
75	31.07	22.24	265.51	150	1.848	0.08	309.83

***Table 1** lamination sheet lengths*

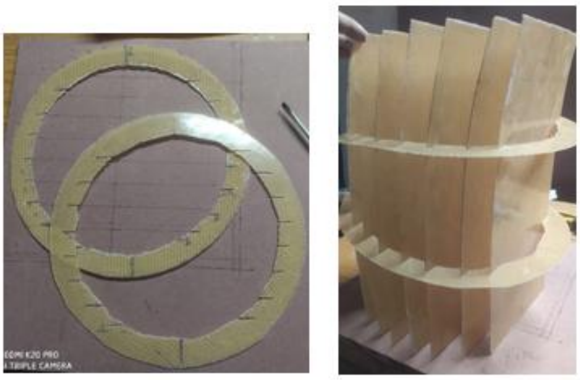

Figure 16 FRP stack sheets

4.3.2 Method 2: FRP sheet stack

- In this method FRP sheets of thickness 1.5mm is used to make stack.
- For 80 Hz system the thermal penetration depth is $2y_0$ = 20mm, $3.5y_0$ = 34.27 mm
- 30mm stack spacing is taken to study.
- Glue gun and fevicol glue did stuck on this sheet therefore circular guides of 15mm were made to fix the FRP sheet in 30mm gaps respectively.
- As the stack spacing is 30mm then the number of stacks = 300/30 = 10 stacks.
- Table for exact FRP sheet lengths to fit into the circular guides.

Number of stack	Height of stack (mm)	Angle of the stack	Cutting length (mm)	Width of stack needed
1	20	60.07	75.16	149.66
2	50	41.81	38.19	223.6
3	80	27.81	17.33	265.32
4	110	15.46	5.43	289.13
5	140	3.82	0.333	299.33

***Table 2** FRP stack sheet dimensions*

- ➢ As method 1 required 60 stacks to fabricate it got very time consuming, therefore **method 2** was used having 10 stacks which was easy to fabricate the whole stack.
- ➢ Difficulty faced during fabrication of FRP stack
  - o Glue gun glue, fevicol, or any other glue was not sticking perpendicular to the surface of the stack.
  - o The FRP sheet is deformed in curved shape and it's very difficult to shape it straight.
  - o Lots of force is require to cut the FRP sheet, I recommend to buy larger cutting scissor so that it's easy to cut the sheet.
  - o I used hand grinder with metal cutting disc to cut the FRP sheet, while doing so it produced lots of powered dust which caused skin rashes for one day. I would recommend to cover skin fully and wear mask and glasses while cutting with grinder.
- ➢ Causes that led to discard method 1 of stack fabrication are:
  - o Stack fabrication of 60 stacks method was very time consuming.
  - o Smaller stack spacing which led to complex fabrication.
  - o 40 W glue gun device which melted glue slowly.

Figure 18 Acrylic Stack

Figure 17 Stack in resonator

4.3.3 Acrylic stack fabrication by method 2

- properties of Acrylic stack
  - o Thermal conductivity: 0.19 W/mK
  - o Density : 1.19 g/cm^2
  - o Modulus of elasticity :3300MPa
- Stack spacing: 15mm, Stack length: 350mm
- Number of stacks considering the thickness of the sheet and circular guide thickness(15mm) 15sheets

Number of stack sheet	Sheet position (mm)	Sheet width (mm)
1	32	165
2	49	205
3	66	235
4	83	255
5	100	270
6	117	280
7	135	287
8	151	289
9	168	285
10	185	280
11	202	270
12	219	255
13	236	235
14	253	205
15	270	165

Figure 19 Amplifier


Figure 20 Digital thermometer


Figure 21 Power Supply

Lamination sheets are soft and very flexible to work with.

- Amplifier: XM-N1004 Sony
  - Frequency response: 5 Hz to 50 KHz
  - Noise ratio 100 db
  - Operating voltage : 12 v DC, 32A
  - Output max power : 1000 W
  - RMS power output: 175 W, 4 Ω bridge mode
- Power supply: 12V 50A 600W DC
- Auxiliary components:
  - Digital Thermometer:
    - Temperature measurement: -50°C to + 300°C
    - Temperature accuracy: ±1°C


Figure 41 Experimental setup

V. EXPERIMENTAL RESULTS AND DISCUSSION

- The Fabricated stack as per design was placed into the resonator at different lengths of λ/8 = 0.5562m, λ/14 = 0.3178m, λ/20 = 0.2225m. λ = 4.45m
- Holes were made on the resonator across the stack for digital thermometer.
- The temperature readings across the stack at stack position λ/8 = 0.5562m is given in table 4

Time	**Cold side of stack (side close to driver) ^{0}C**	**Hot side of stack (side close to resonator open end) ^{0}C**	**Temperature difference ΔT**
1 min	32.2	32.5	0.3
2min	32.2	32.5	0.3
3min	32.0	32.6	0.6
4min	32.0	32.8	0.8
5min	31.8	32.9	1.1
6min	31.8	32.9	1.1
7min	31.6	33.0	1.4
8min	31.5	33.0	1.5
9min	31.5	33.0	1.5

10min	31.5	33.0	1.5

Table 3 *temperature readings across the stack at stack position λ/8*

- The temperature readings across the stack at stack position λ/14 =0.3178m is given in table 5

Time	**Cold side of stack (side close to driver) ^{0}C**	**Hot side of stack (side close to resonator open end) ^{0}C**	**Temperature difference ΔT**
1 min	32.2	32.2	0
2min	32.1	32.5	0.4
3min	32.0	32.6	0.6
4min	31.9	32.8	0.9
5min	31.9	32.9	1.0
6min	31.8	32.9	1.1
7min	31.7	33.0	1.3
8min	31.4	33.2	1.8
9min	31.3	33.3	2
10min	31.3	33.3	2

Table 4 the temperature readings across the stack at stack position λ/14

- The temperature readings across the stack at stack position λ/20 = 0.2225m is given in table 6

Time	**Cold side of stack (side close to driver) ^{0}C**	**Hot side of stack (side close to resonator open end) ^{0}C**	**Temperature difference ΔT**
1 min	32.0	32.2	0.2
2min	32.1	32.6	0.5
3min	32.0	32.8	0.8
4min	31.8	33.1	1.3
5min	31.7	33.3	1.6
6min	31.5	33.4	1.9
7min	31.4	34	2.6
8min	31.2	34.1	2.9
9min	31.2	34.2	3
10min	31.1	34.3	3.2

Table 5 *the temperature readings across the stack at stack position λ/20*

- The maximum experimental temperature difference obtained is ΔT =3.2^{0}C at stack position λ/20 close to driver.
- The experimental results shows that:
  - At positions λ/14 and λ/8, the thermoacoustic effect gets low in stack as keeping stack further away from the driver.
  - The performance of the system increases when stack is placed closer to driver.
- It was observer that the resonator vibrated highly at 80 Hz, as the resonator was designed to resonate at 80 Hz, reverberations from the building were audible at 50% volume of driver.
- Analytical results from Delta EC gave the following conclusions:
  - Acoustic power increases when stack thickness decreases or when frequency of the driver increases.
  - Temperature difference around the stack increases:
    - When the driver frequency gets lower
    - When Stack length increases
- For atmospheric pressure thermoacoustic refrigerator, the cost of the project was feasible to fabrication but for high pressure system many more components needed like pressure vessel instead of resonator, pressure seals gaskets which would increase the cost of the project and require sufficient funding.
- This study and setup can be used for further research for high powered thermoacoustic device.

VI. CONCLUSION

- The maximum experimental temperature difference obtained is ΔT =3.2^{0}C at stack position λ/20 close to driver.
- The experimental results shows that:
  - When stack is placed closer to driver the temperature difference rises.
  - The performance of the system increases when stack is placed closer to driver.

- The maximum analytical temperature difference obtained in software Delta EC is ΔT = 54^0 C at setup parameters:
  - Stack length = 225mm
  - Frequency of driver= 80Hz
  - Resonator length = 1.1125mm
  - Stack position λ/20 = 222.5mm
- The conclusion of analytical results are:
  - Frequency of driver is proportional to acoustic power
  - Stack plate spacing is inversely proportional to frequency of driver
  - Stack length is directly proportional to temperature difference across the stack
  - Frequency of the driver is inversely proportional temperature difference of stack

Future Scope:

- Stack fabrication was the most difficult work than resonator fabrication and speaker box construction, it is recommend future studies to give most of time to stack fabrication.
- This setup can be optimized furthermore with rigid and strong stack material such as acrylic sheet.
- As thermoacoustic effect is sensitive to pressure oscillations, it is recommended to fabricate a high pressure resonator up to 10 bar.

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Nomenclature