# Development of Standing Wave Thermo Acoustic Prime Mover

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**Abstract-**Recent technological advance has brought about environmental destruction. In particular, Cooling systems are identified as one of the cause of environmental problems. In existing cooling systems refrigerant used not only destroys Ozone in the atmosphere but also causes of Global Warming due to green house effect.

Recent studies tend towards construction of a practical cooling system based on the thermoacoustic effect. The thermoacoustic effect induces a mutual energy conversion of sound energy and heat energy. The sound pressure generated in the thermoacoustic device is increased with increasing supplied heat energy. By applying the thermoacoustic effect it will be possible to construct a new epoch-making cooling system with many unique advantages: effective use of waste energy, no use of poisonous cooling media and no moving parts

**Index Terms-** Thermoacoustic1, Cooling2, Heat3

## 1. INTRODUCTION

During the past two decades, there has been an increasing interest in the development of thermoacoustic cooling and heating for various applications. Thermoacoustic refrigerators can be constructed such that they use only inert gases, which are non-toxic.

Thermoacoustic engine uses high-amplitude sound waves in a mixture of harmless gases to create oscillations in pressure, temperature and displacement, which are used to pump heat. Although the temperature oscillations are small, research during the past two decades has shown that "Thermoacoustic" effects can be harnessed to produce powerful and efficient heat engines, including heat pumps and refrigerators. Thermoacoustic engines typically have no moving parts. Some have a single oscillating part (such as the diaphragm in a loudspeaker), which needs no lubrication or sliding-seals that are subject to wear. Thus, these engines have the potential to be simple, reliable and cost less to operate. They can be mass-produced using current production methods and use harmless gases found naturally in the environment.

High amplitude sound waves are generated inside a specially-shaped cavity called a resonator, pressurized to several atmospheres. The temperature differences occur across a stack of plates that are positioned between hot and cold heat exchangers, where the heat is removed or added to the system. TA units can be powered by low voltage from batteries or biogas fuels, They can convert almost any heat source, like the waste heat from an internal combustion engine, directly into sound waves that can be used to pump heat.

## 2. PROJECT REVIEW

### 2.1 INTRODUCTION AND BACKGROUND

The history of thermo acoustic energy conversion has many interwoven roots, branches and trunks. It is a complicated history because invention and technology development outside of the discipline of acoustic have sometimes proceeded fundamental understanding at other times fundamental science has came first Root develop the mathematical describing acoustic oscillation in a gas in a channel with an axial temperature gradient, with lateral channel dimensions of the order of the gas thermal penetration depth (typically=1mm). The problems have been invented by rayleingh and Kirchhoff, but without quantitative success. In root's time, the motivation to understand the problem arose largely from the cryogenic phenomenon known as Taconic oscillation when a gas filled tube is cooled from ambient temperature to a cryogenic temperature, the gas sometimes oscillation spontaneously, with large heat transport from ambient to the cryogenic environment. Yazaki demonstrated convincingly that Rott's analysis of Tacnis oscillations was quantitatively accurate. The century earlier, Rayleigh understood the qualitative features of such heat driver oscillations 'If heat be given to the air at the moment of greatest condensation (greatest density) or be taken form it at the movement of greatest rarefaction, the vibration is encouraged' 'he had

studied sondhauss oscillation the precursor, to taconis oscillation.
Applying Rott's mathematics to a situation where the temperature gradient along the channel was too weak to satisfy Rayleigh's criterion for spontaneous oscillation, Hofler invented a standing wave thermoacoustic refrigerator, and demonstrated again that Rott's approach to acoustic in small channels was quantitatively accurate. In this type of refrigerator, the coupled oscillation of gas motion, temperature, and heat transfer in the sound wave are phased in time so that heat is absorbed from a load at a low temperature and waste heat is rejected to a sink at a higher temperature.

Meanwhile, completely independently, pulse tube refrigeration was becoming the most actively investigated area of cryogenic refrigeration. This development began with Gifford's accidental discovery and subsequent investigation of the cooling associated with square wave pulses of pressure applied to one end of the pipe that was closed at the other end. Although the relationship was not recognized at the time, this phenomenon shared much physics with Hofler's refrigerator. Mikulin's attempt at improvement in heat transfer in one part of this basic pulse tube refrigerator lead unexpectedly to a dramatic improvement of ***performance, and Radebaugh released that the resulting orifice pulse tube refrigerator was infact a variant of the sterling cry cooler.***

2.2 BASIC PRINCIPLE OF THERMOACOUSTIC EFFECT

One of the earliest inventions of thermoacoutic effect was done by Rijke. He demonstrated the creation of sound using heat using Rijke's tube.
Rijke's tube turns heat into sound, by creating a self-amplifying standing wave. P. L. Rijke was a professor of physics at the Leiden University in the Netherlands when, in 1859, he discovered a way of using heat to sustain a sound in a cylindrical tube open at both ends. He used a glass tube, about 0.8 m long and 3.5 cm in diameter. Inside it, about 20 cm from one end, he placed a disc of wire gauze as shown in the figure below. Friction with the walls of the tube is sufficient to keep the gauze in position. With the tube vertical and the gauze in the lower half, he heated the gauze with a flame until it was glowing red hot. Upon removing the flame, he obtained a loud sound from the tube which lasted until the gauze cooled down (about 10 s). It is safer in modern reproductions of this experiment to use a Pyrex tube or, better still, one made of metal.
Instead of heating the gauze with a flame, Rijke also tried electrical heating. Making the gauze with electrical resistance wire causes it to glow red when a sufficiently large current is passed. With the heat being continuously supplied, the sound is also continuous and rather loud. Rijke seems to have received complaints from his university colleagues because he reports that the sound could be easily heard three rooms away from his laboratory. The electrical power required to achieve this is about 1KW.

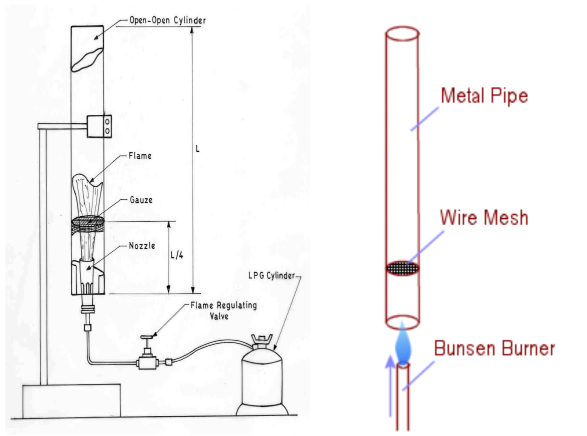



**Fig 1: Rijke Experiment: A simple construction of the Rijke tube, with a wire meshes in the lower half of a vertical metal pipe. The tube is suspended over a Bunsen burner.**

**2.3 ACOUSTIC WAVES IN TUBE**

Consider an acoustic energy source (e.g., a tuning fork) placed near one of the ends of an open-open tube as shown in figure. A part of the acoustic energy produced by such a source enters into the tube in the form of a 'travelling acoustic wave'. As this wave travels through the tube, it loses some of its energy due to friction. When it reaches the other end of the tube, a part of the remaining energy reflects back into the tube, again in the form of a travelling acoustic wave. The rest of the energy transmits through the open tube boundary and comes out of the tube. So, as shown in Figure, in the presence of an acoustic energy source, the part of the acoustic wave that reflects from the open end interacts with the incoming traveling wave to produce what is termed as a standing wave or a stationary wave.
The positions where the magnitude is zero are termed as nodes while the positions with maximum amplitude are termed as antinodes. One must also note that the oscillation at every point along the tube is in phase. Thus, unlike traveling waves where the waveform moves ahead ('travels') in time, for a standing wave, the waveform appears to be stationary or standing.
The fundamental mode is the one with the lowest possible frequency and the largest wavelength that satisfies the boundary conditions. In this case, the largest wavelength is clearly $\lambda$=2L, where L is the length of the tube. For the fundamental mode, the acoustic pressure has one peak at the middle of the

tube while the ends of the tube always have zero acoustic pressure.

The acoustic velocity node and antinodes are exactly the reverse of those for the pressure. It is usually the fundamental mode that is heard in Rijke tube experiments

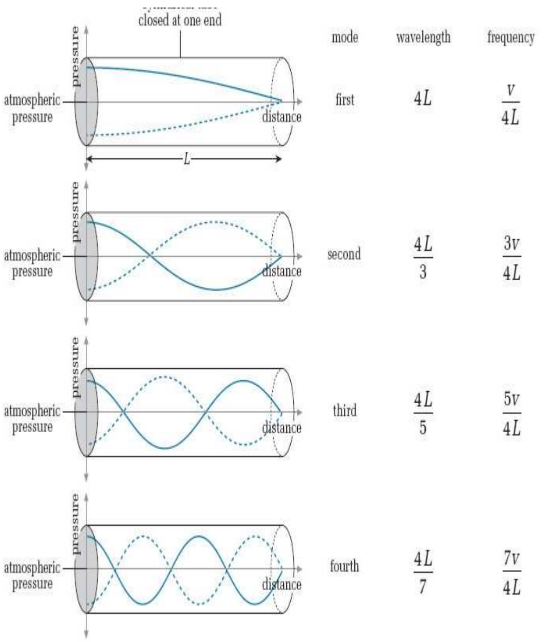



**Fig 2: shows the change of wave length in a closed tube**

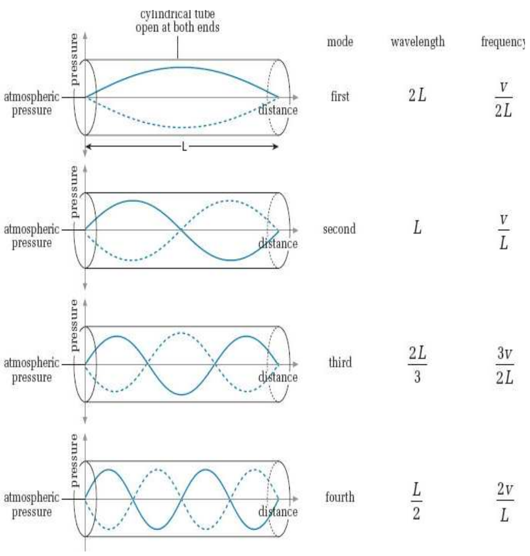



**Fig 3: shows the change of wave length in a open tube**

2.4 WORKING PROCEDURE

The gas in the heater section heats up the gas rises and molecules start moving randomly due to decrease in density. These molecules collide each other and produce sound. Sound waves are nothing but the pressure waves. As these waves passes through the narrow channel in stack the medium far from the channel wall undergoes an adiabatic compression change and the medium close to the wall undergoes an isothermal compression change. When the medium is in isothermal compression change, heat energy is exchanged between the channel wall and the medium. This means that energy conversion between sound energy and heat energy is introduced in the stack. Thus cooling of gas takes place in stack. These waves are then moved to ambient heat exchanger where the heat from the waves coming out of stackpart is removed. The cooled pressure/sound wave's travel along the resonator column at the end of the resonator column tapper section is provided to reduce the viscous loss.

## 3. MAJOR COMPONENTS OF THERMOACOUSTIC ENGINE

1. Hot buffer
2. Hot end heat exchanger
3. Stack
4. Cold end heat exchanger
5. Resonator

## 4. PRELIMINARY DESIGN OF STANDING WAVE ENGINE

Here we concentrate on design of individual parts of thermoacoustic engine, which are as follows

- Hot buffer
- Heater
- Stack
- Heat Exchangers
- Resonator

**Working Fluid**

The working fluid plays a paramount role in the performance of cooler. To obtain lower frequency pressure wave nitrogen is obviously better choice than helium for its sound speed is about 1/3 of that helium. However helium has advantage of its lower boiling temperature which will enable its application for very low temperatures. Although mixture of inert gases can be tried out, in the present investigation **nitrogen** is used as the working medium as our target temperature is not too low, 100K

1. Hot buffer

The Hot Buffer being the basic constituent in the system is made of steel and by considering all the previous experiments the length of the Hot Buffer is taken as 100mm and diameter is chosen as 60mm. As the wall thickness plays a vital role in the performance, the minimum available 1.5mm is chosen. It is an additional volume provided before the heater section which ensures that the acoustic waves completely travel the entire length of the stack assembly.

## 2. Heater

The heating section is designed for a maximum heating capacity of 1kw using external heating. Internal heater such has with porcelain bobbins is avoided mainly due to the fact electrically leads to these heaters have to be taken through glass to melt seals feed through from outside. These are quite difficult to procure and moreover the heater section temperature is quite over $500^0$ c which will create problem of sealing inside the pipe in the heating section number of thin parallel copper sheets of around 0.3mm thick are arranged with the gap spacing 6mm. This provides narrow channel for the gas passage. The length of the heater is taken as 100mm and diameter 60mm.

## 3. Stack

It is the core part of the system, is made of stainless steel by considering all the previous experiments the length of the stack is taken as 280mm, and diameter is chosen as 56mm. The stack is developed by placing stainless steel parallel to one another of thickness 0.3mm andspace between them is provided by placing spacers of thickness 0.3mm. This stack assembly is placed inside a tube of diameter 56mm and of lengths of 280mm, at their respective positions.

The primary constraint in designing the stack is the fact that stack layers need to be a few thermal penetration depths apart, with four thermal penetration depth being the optimum layer separation *. The thermal penetration depth $\delta_k$can be expressed as $\delta_k = \pi f \rho c_p$

where k, ρ and $c_p$are the properties i.e. thermal conductivity, density and isobaric specific heat of working gas at the mean temperature and f is the frequency of the standing wave generated. The thermal penetration depth is defined as the distance that heat can diffuse through a gas during the time $t=1/\pi f$

If stack layers are too far apart the gas cannot effectively transfer heat to and from the stack walls. If the layers are too close together viscous effects hamper the motion of the gas particles.

<u>Thermal penetration depth.δk</u>

$\delta k = \sqrt{[2k/\rho\omega Cp]}$

Where k=thermal conductivity=0.083 W/m-K

P= 1.6883 kg/m3

Cp = 1043 J/kg/K

$\omega = 2\prod f = 2x3.14x\ 500 = 3140$ rad/sec

Properties are evaluated at mean temperature of stalk for nitrogen gas=350+50]/2=200

This works out to 0.07823 mm, Normally passages for gas is taken as 4x δk=0.0313mm

As this value is too small, a practical value of 0.8 mm is chosen from the fabrication point of view

## 4. Heat Exchanger

It is component located just after the stack section to remove heat from the gas. The Heat exchanger consists of two concentric tubes; both tubes being 56mm diameter and, the lengths of these tubes are 60mm for Cold end H.E and 100mm for Hot end H.E. The tube is filled with copper sheets of thickness 0.3 mm and space between them is being 6mm for better thermal contact. The space between smaller and larger tube acts as water jacket.

## 5. Resonator

It is a key component of the system is made up of stainless steel. The length of the resonator column is 4000mm, diameter of 38mm and thickness of 2mm. It is connected to a taper section i.e. reducers. Resonator column is the place where Standing Waves are generated. It is used to determine the Working Frequency and influence the thermal performance.

The purpose is to decrease the operating frequency of the thermo acoustic prime mover. For half wave length system, the frequency can be expressed as:

$$f = a/\ 2L =$$

Where f denotes frequency, a is the sound speed, L is the resonator length, are the gas properties and T is the temperature. The frequency depends on the resonator length and sound speed of the working fluid. Longer the resonator length and lower is the sound speed, lower will be the frequency of output wave and vice versa. However, this requires a very long resonator length and very closely arranged stack which will result not only viscous losses and occupies a large space. Hence operating frequency of output wave of the engine is higher than the required frequency of the pulse tube cooler in most of the cases.

For nitrogen gas which is chosen as the working medium, properties are

=1.4

R=280 J/kg/K

T (Avg) 400+273=673K
Required lower frequency for driving Pulse tube = 50 c/s
Generated higher frequency from prime movers= 500 c/s
Length of the resonator section required
L= =4.7m
Actually 4 meter long resonator section is chosen.

4.6. Reducers

A reducer is the component in a pipeline that reduces the pipe size from a larger to a smaller bore (inner diameter).The length of the reduction is usually equal to the average of the larger and smaller pipe diameters. This is used to connect the prime mover sections to resonator sections. Material used for the reducer is stainless steel .Dimensions are as follows, diameter at smaller end is 38mm,bigger end is 68.5mm and length is 63mm .The taper section is provided to reduce

5. CONSTRUCTION OF STALK AND HEAT EXCHANGERS

## 5.1 Stalk construction

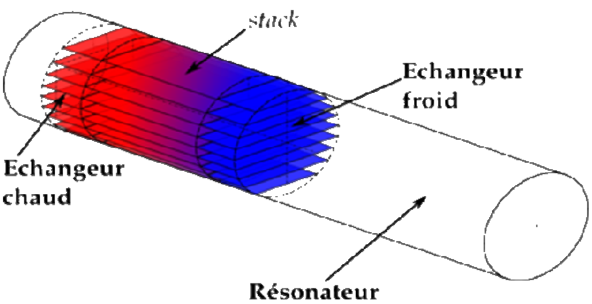
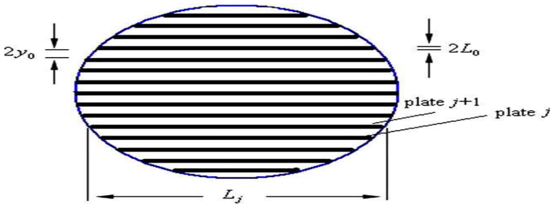
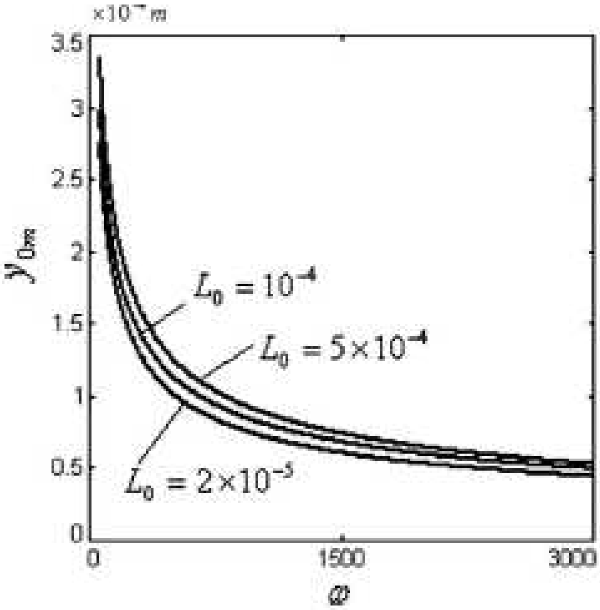



**Fig: Arrangement of stack, hot end heat exchanger and cold end heat exchanger**




The construction of the stalk will be on the similar line as reported by Feng Wu et a

From the results published by FengWui for plate thickness of 0.3 mm (Lo=0.15 mm) and frequency of 500 c/s, optimum thickness of spacer will be 1.6 mm. However this value is far higher than 4 times the thermal penetration depth for nitrogen. Initially stalk spacer thickness of **0.3** was selected lowest available. This configuration posed several problems:

a. The gap between the plates was too narrow and as such the consecutive plates were almost touching in several places
b. It is impossible to weld the stalk spacer with plates as the material of s.s. was melting
c. The plate and spacer could not be brazed by gas welding as brazing temperature is much lower compared to operating temperature of the heater

From these limitations spacer thickness of 0.8 mm was used in between stalk plates.

The same argument holds good selection of stalk plate thickness and spacer thickness for copper sheet in hot and cold end heat exchangers.

5.2 Calculation of number of plates

The inside diameter of the stalk section chosen is 52 mm. In addition a Thin walled stainless steel sleeve with wall thickness of 1 mm is used to assemble the stalk plate separately.
Thus actual inside of stalk section is 50 mm ( R).
In the present design, thickness of plates is 0.3 mm and spacer thickness is 0.8. Hence total number of plates required will be 50/(0.3+0.8) = 44
With one plate at the center, number of plates above the center plate will be 22 and 22 below the center plate.

Width of individual plates are Lj ( calculated from geometrical consideration )

$$L_j = 2x\sqrt{[\{(2\ j\ )\ (y_o+L_o)\}^2+R^2]}$$

Where $2y_o$ = thickness of spacer, $2L_o$ = Thickness of plates, j =number of plates above or below center plate under consideration for calculation of width. As per the calculation width of each individual plate is calculated and tabulated as given below

| Plate no | Height above central diameter( mm) | Width of plate | Plate no | Height below central diameter | Width of plate |
|---|---|---|---|---|---|
| j = + 1 | 1 . 1 | | j = - 1 | 1 . 1 | |
| j = + 2 | 2 . 2 | | j = - 2 | 2 . 2 | |
| j = + 3 | 3 . 3 | | j = - 3 | 3 . 3 | |
| j = + 4 | 4 . 4 | | j = - 4 | 4 . 4 | |
| j = + 5 | 5 . 5 | | j = - 5 | 5 . 5 | |
| j = + 6 | 6 . 6 | | j = - 6 | 6 . 6 | |
| j = + 7 | 7 . 7 | | j = - 7 | 7 . 7 | |
| j = + 8 | 8 . 8 | | j = - 8 | 8 . 8 | |
| j = + 9 | 9 . 9 | | j = - 9 | 9 . 9 | |
| j = + 10 | 1 1 . 0 | | j = - 10 | 1 1 . 0 | |
| j = + 11 | 1 2 . 1 | | j = - 11 | 1 2 . 1 | |
| j = + 12 | 1 3 . 2 | | j = - 12 | 1 3 . 2 | |
| j = + 13 | 1 4 . 3 | | j = - 13 | 1 4 . 3 | |
| j = + 14 | 1 5 . 4 | | j = - 14 | 1 5 . 4 | |
| j = + 15 | 1 6 . 5 | | j = - 15 | 1 6 . 5 | |
| j = + 16 | 1 7 . 6 | | j = - 16 | 1 7 . 6 | |
| j = + 17 | 1 8 . 7 | | j = - 17 | 1 8 . 7 | |
| j = + 18 | 1 9 . 9 | | j = - 18 | 1 9 . 9 | |
| j = + 19 | 2 1 . 0 | | j = - 19 | 2 1 . 0 | |
| j = + 20 | 2 2 . 1 | | j = - 20 | 2 2 . 1 | |
| j | 2 3 . 2 | | j | 2 3 . 2 | |

5.3 Fabrication and Assembly of Stack and Heat Exchangers

Fabrication of stalk and heat exchanger is the most challenging aspect the development of the cooler.

Lot of problems were faced right from cutting of materials and welding of the stack plate to spacer plates . Several specimens were tried out as lower thickness spacer (0.8 mm) was melting and finallya spacer thickness of 0.8 mm x 4mm (2 Nos) per passage was chosen to facilitate argon arc welding. The stack assembly was further assembled in a S.S. of 1mm wall thickness and of length of 288 mm. Similarly for fabrication procedure was followed for hot end and cold end exchanger.Same plate thickness of 0.3 mm was welded to copper spacer material of 0.8 mm

6. FABRICATION

## 6.1SELECTION OF MATERIALS

All the major outer body of the Prime mover section and 'Resonator section, flanges, end coverscold end heat exchanger jacket, reducers are made of stainless steel 304 as it is free from corrosion, low thermal conductivity and good weldabilty .All pipe sections are seamless as they are required to withstand high pressure and high temperature. Stainless steel 304 is also used for construction of Stalk plates and spacers. The heat exchanger plates inside the section and spacers are made of copper because we good thermal conductivity for heat reception from heaters and heat rejection to cooling water. Neoprene O rings are used to seal the assembly of flanges between heat exchanger section and resonator.

## 6.2 Bill of Materials

| Sl. No | Part | Material | Specification | No |
|---|---|---|---|---|
| 1 | Hot Buffer | S.S. Tubin | 100 mm X 4 mm X 100 mm | 2 |
| 2 | Heaters | Nichrom | 100 mm X 100 mm,1000W | 2 |
| 3 | Stack | S.S. Sheet & copp | 52 mm X 0.3 mm X 288 mm<br>56mm X ( | 2 |
| 4 | Flange | S.S | 130 mm O.D X 12 mm thick | 4 |
| 5 | Water Jacke | S.S. Tubin | Inner Jacket-<br>50mm X<br>Outer Jac<br>70 mm X | 2 |
| 6 | Resonator | S.S Tubing | 36mm X 2mm X 4000mm | 1 |
| 7 | Conical Reducers | S.S | 38 id x 68.5 od x 63mm long | 2 |
| 8 | Straight couplers | S.S | ¼" BSP | 6 No |
| 9 | End Plates | | 52 mm dia x6 mm thick | 2 |
| 1 | Thermocouples 8nos | Chromal -Alum | 28 gauge x 0.5 met each | 8 |
| 1 | Digital Temperature Indicato | | One decimal place mV | 1 |
| 1 | PID controlle<br>For pro | - | With SSR output | 2 No |
| 1 | Bourdon Tube Pressure gaug | Brass | 0-50 bar | 1 |
| 1 | Charging Ball Valve | S.S | ½ " | 1 |

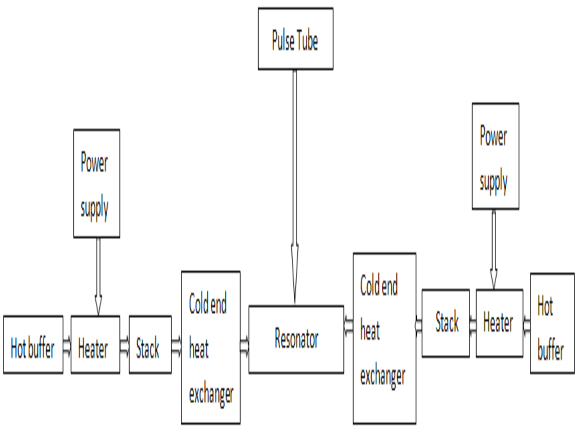
**6.3 Machining:** The pipe sections procured are roughly turned on the lathe. The thickness of stalk section is reduced 2 mm wall thickness by turning with a mandril inside. This is provided to reduce conduction heat transfer through the stalk pipe section. Flanges with proper o ring groove as per B..S standard are machined by facing .

**6.4.Tungsten inert gas (TIG) Welding:** During the fabrication of thermo acoustic prime mover stainless parts to be welded are welded using Argon Arc TIG welding It is used to weld the flange and the heater section, Stack section tube with another flange; resonator tube, conical section and reservoir which are of same material. Argon Arc welding has the advantage of fusing the components and provides a leak proof joint between the components used.

## 5.5. Temporary Fastening:

Fastening of each component is done for assembly for prime mover by stainless steel bolts and nuts.As thermocouples are connected to cold end and hot end, the connection may be lost due o choke in the system or break down of thermocouple itself, the system should be flexible enough to dismantle the flange in order to check whenever necessary. Hence, the flanges are connected by bolting. In order to ensure leak proof joint between the flanges, a high temperature rubber gasket is provided as a seal between them.

## 6.5 Block Diagram




## 6.6 Pressure Testing:

Before starting the actual experimentation, the system should undergo pressure test tocheck for air leakages. Hydraulic pressure testing was carried out using hand pump for pressure up to 40 bar as indicated by the bourdon tube pressure gauge. A hydrostatic test is a way in which leaks can be found in pressure vessels such as pipelines and plumbing. The test involves placing water, which is often dyed for visibility, in the pipe or vessel at the required pressure to ensure that it will not leak or be damaged. It is the most common method employed for testing pipes and vessels. Using this test helps maintain safety standards and durability of a vessel over time. Newly manufactured pieces are initially qualified using the hydrostatic test. They are then continually re-qualified at regular intervals using the proof pressure test which is also called the modified hydrostatic test. Hydrostatic testing is also a way in which a gas pressure vessel, such as a gas cylinder or a boiler, is checked for leaks or flaws. Testing is very important because such containers can explode if they fail when containing compressed gas.

CHAPTER 7
COMMISSIONING AND TESTING

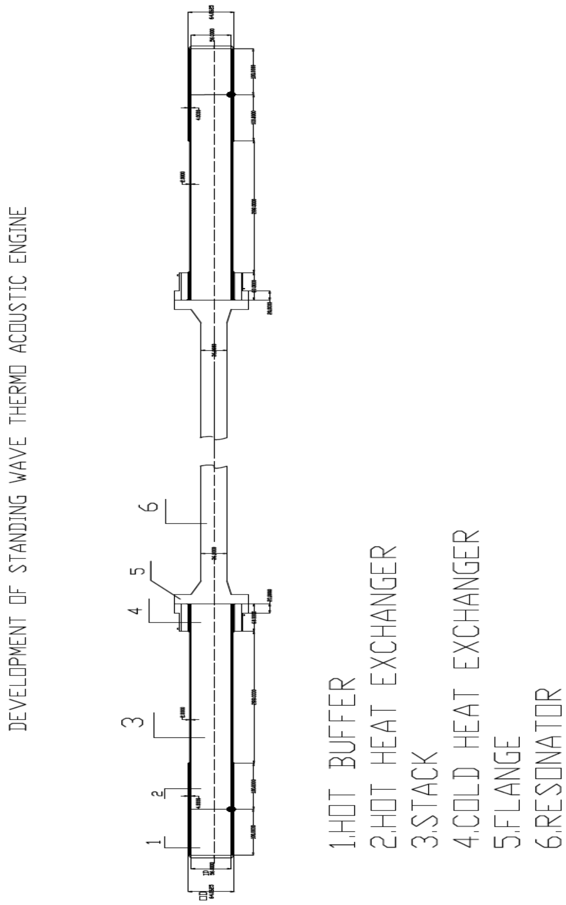
## 7.1Instrumentation and Controls:

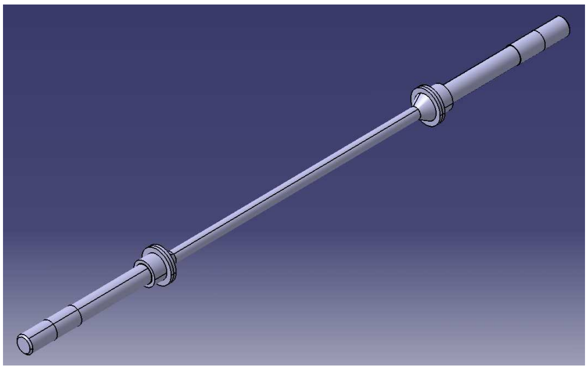
The following Instrumentation and Controls are provided for commissioning and testing the equipment

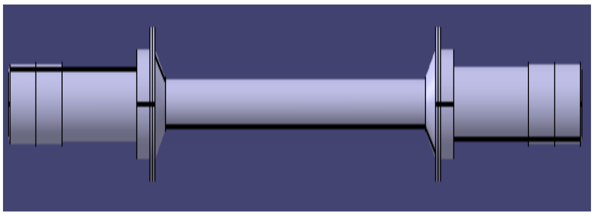
1. Bourdon Tube Pressure Gauge ( 0-50 bar)
2. Digital Temperature Indicator (LCD display) with multipoint thermocouple selector switch
3. PID Controller for programmable heating with temperature display
4. Voltmeter and Ammeter for measurement of power supplied to heaters
5. Nitrogen gas pressure Regulator 0-16 bar ( Two stage)
6. ChromalAlumal Thermocouples for measurement of temperatures at the beginning of heater section, stack, cold end heat end exchanger and exit section of C.W. heat exchanger for both the engines ( 8 Nos)
7. Electrical accessories such as main switches for both heaters, MCB etc.

## CHAPTER 8

## ASSEMBLY DRAWING OF THERMOACCOUSTIC PRIME MOVER



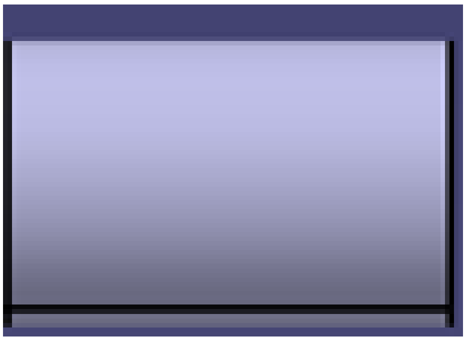




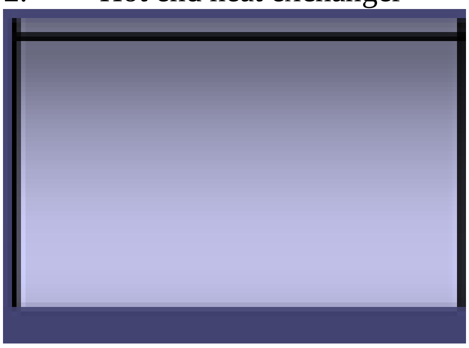
Title of the part

PART DETAILS

1. Hot buffer

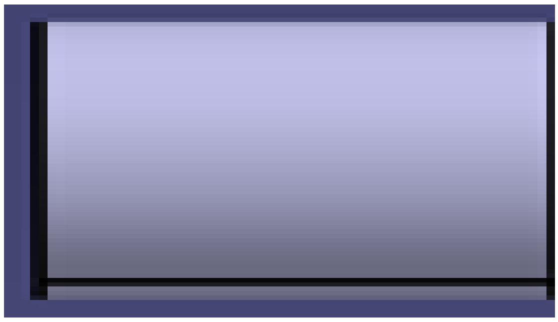


2. Hot end heat exchanger

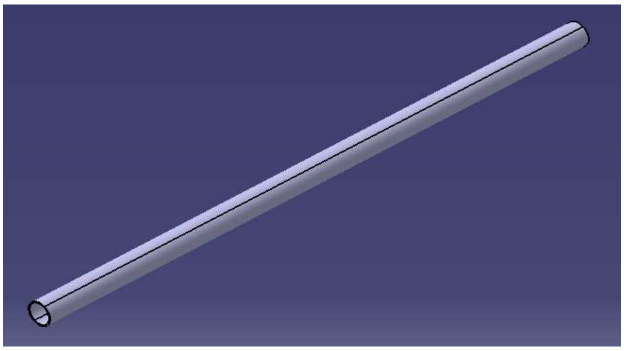


3. Stack

4. Cold End Heat Exchanger



5. Resonator



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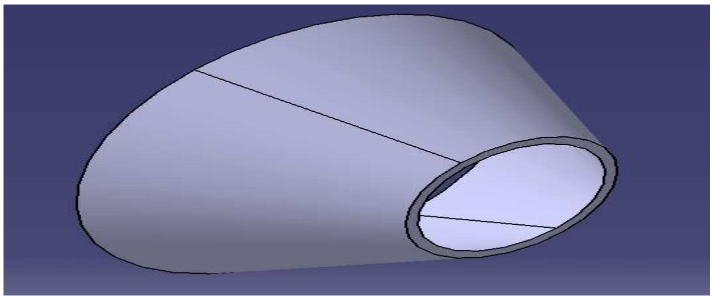
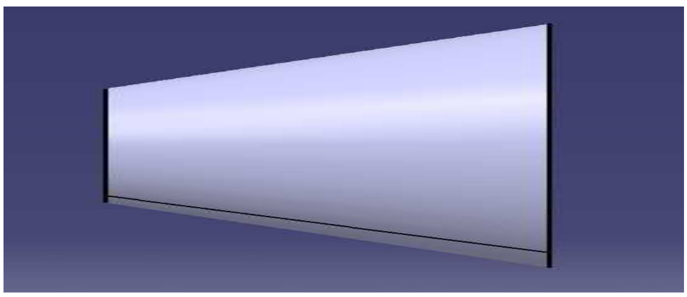
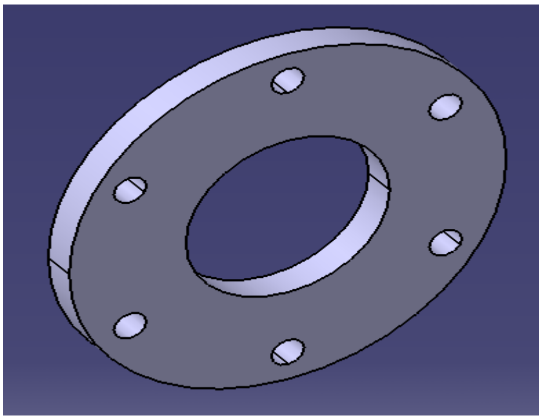
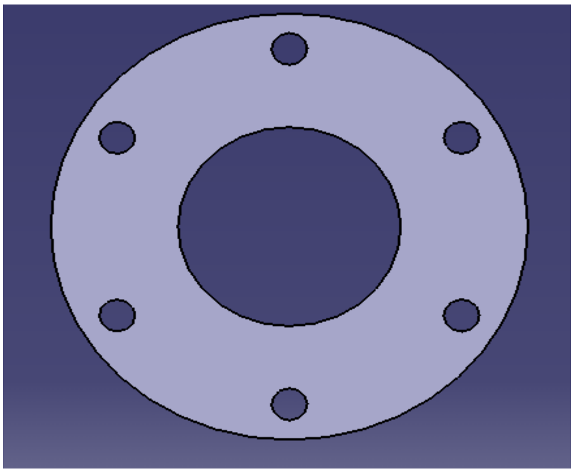


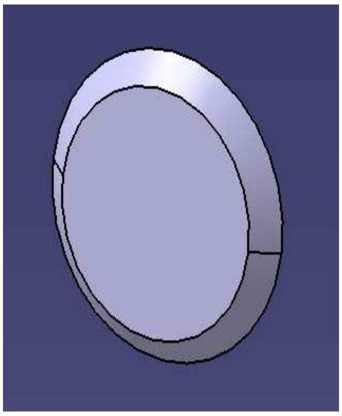


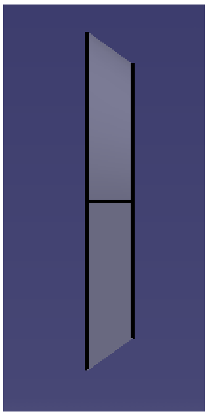
## 7. FLANGES





## 8. END PLATES





## 9.CONCLUSIONS AND SCOPE FOR FUTURE WORK

Development of thermoacoustic prime mover based on standing wave concept was taken up. The scope of our work was limited to fabrication of a prime mover which posed several challenges during development work. Although prime mover is just ready for further investigation, lot of fine tuning is required especially in the construction of stalk and heat exchangers. Due to paucity of time detailed testing could not be carried. Initial testing can be carried by integrating an existing pulse which is of double inlet and orifice time. The work assigned is a part of on going sponsored project in the department . There is adequate scope for future work by carrying out detail investigation with parametric variations and performance study.

**Scope**: The project has given us an opportunity to study a new emerging thrust area in refrigeration and practical fabrication problems and to overcome the same.

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