THERMAL ACOUSTIC REFRIGERATION: A REVIEW

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Abstract: Thermoacoustic is the process of heat transfer from one end to another wherein the surface is hot at one end and cold in the other. A thermal Acoustic Refrigerator uses sound as a coolant and eco-friendly gases as working fluids. Refrigerators are used widely to cool substances kept in it or to keep the surrounding at a lower temperature than the atmosphere. This is mainly done using the HCFC's(1) CFC's(2) i.e. the freons(3) that are mainly responsible for ozone layer depletion. In order to solve this major environmental hazard, it is very important to research more on the eco-friendly refrigeration techniques like the one being discussed in the paper. This paper presents the comparison of the various parts and design parameters used in making a low-capacity Thermal Acoustic Refrigerator (TAR). Resonator (4) shape, stack material and design are the subject of this research. This experiment shows the variation in the performance of TAR when the above-mentioned parameters are altered. It also explores the area of research to be done in order to improve the efficiency of TAR.

Keywords: TAR- Thermal Acoustic Refrigerator, CFC-Chlorofluorocarbons, HFC – Hydrochlorofluorocarbons.

1. INTRODUCTION

Refrigeration is a process of cooling the system and keeping its temperature lower than it's surrounding. It is an important aspect of both domestic and commercial sector. A standard refrigerator has mechanical elements which include compressor, condenser, expansion valve, throttling device and an evaporator. Additionally, the fridge uses refrigerant, a substance used to provide cooling effect. R-134A, R-410A, CFCs, HCFCs, HFCs are some of the commonly used refrigerants. But this system works at the cost of environment, the leakage of refrigerant gases into the environment causes ozone depletion, global warming and raises CO_2 emissions.

Keeping the environment in mind, this new technology of Thermoacoustic refrigeration is one of the most promising areas of research. A **TAR** uses sound to provide the cooling power. Sound travels as longitudinal waves and therefore, the interconversion of heat and sound energy takes place due to compression and rarefaction of these waves.

Heat transfer takes place across the stack of the TAR. Heat Exchangers(5) are kept at the either ends of the stack and thus the required cooling/heating is obtained.

2. LITERATURE REVIEW

In 2000, Ben and Jerry's(22)wanted to avoid keeping their ice cream cool at the cost of environment, they decided to partner with researchers at Penn State and they came with the idea of using sound waves to bring the temperature down. They converted sound energy to heat energy similarly vice versa is also possible which is more often called Thermoacoustic Engine. One such small thermoacoustic sound source was invented by Naval Postgraduate School Professor Tom Hofler and Jay Adeff(23). It's known as Hofler tube worldwide, it can produce sound pressure levels upto 149db SPL at 930Hz with heat source being at 308°C.

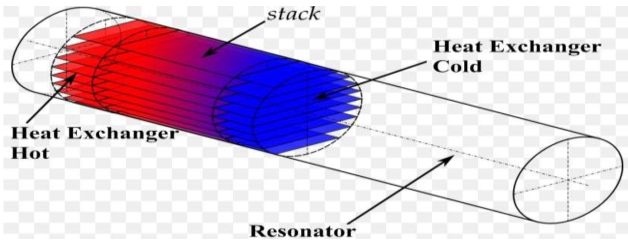
M.E.H Tijani(24) has done significant research in this field, they conducted a series of experiments to find the optimum temperature, stack design, inter plate distance at which a TAR works best. In their research paper, Tijani, H. Zeeger and M.D Waele have concluded that COP of the machine will be high for low prandtl number.

A number of studies have been conducted in Indonesia as well, Iksansetiawan(25) has successfully designed thermoacoustic refrigerator and heaters and also experimented about the porosity effect of the stack. Anastasia used a porous stack to analyse the effect of frequency of operation and the stack length which concluded the frequency to be optimum at 103Hz with max temperature difference of 4.7°C with the stack length being optimal around 6cm.

Design of Thermal Acoustic Refrigerator

The performance of a TAR mainly depends on the following parameters:

- Material parameters- working fluid and stack material.
- Design fabrication- mean pressure, frequency.
- Geometrical parameters- stack length, plate thickness.



A schematic of Thermal Acoustic Refrigerator

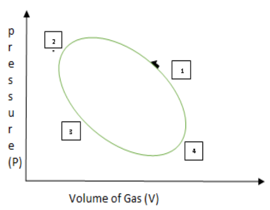
Setup parameters:

- Driver – The Driver of a TAR is responsible for creating sound waves of high intensity. It converts the electrical power to the acoustic power (6). It is attached to the resonator [4] at one end. A function generator is used to set the frequency of sound wave which then gets amplified and is picked up by the loudspeaker.

- Resonator – The device generally is a long tube which is built of various materials. The internal diameter and thickness are varied to obtain different results. One end of the tube is attached with a loudspeaker. The resonator contains the working fluid and therefore, the heating and cooling phenomenon takes place here. Losses kept are minimal to obtain better output.
- Loudspeakers - A vibrating diaphragm or thermoacoustic prime mover which is attached to the resonator. It generates an acoustic wave which makes the gas resonant.
- Stack – A stack is placed inside the Resonator. This is the site where thermal acoustic effect is observed. The temperature gradient is observed here as the acoustic power[6] is converted into heat. It is important to keep factors like the material of stack, thermal conductivity, heat carrying capacity, length of stack, position of stack etc under consideration to obtain an efficient TAR.
- Working Fluid – The working fluid is filled inside the resonator. Noble gases are generally preferred as the working fluid in TAR. It is important to select lighter gases over the heavier gases, which have higher sound velocity and have lower Prandtl number [7].
- Temperature sensors – These devices are used to determine the temperature during the experiment.

3. METHODOLOGY

- **Thermal Acoustic Effect in TAR**
  A standing wave is formed due to the pressure pulsation created as sound wave travels from acoustic driver through the resonator at a particular frequency. The gas in the resonator oscillates in an axial direction. If we place a stationary object which can come in thermal contact with the gas, heat is transferred. This is the result of pressure pulsation coming in contact with the oscillating gas particles.
  Heating and cooling takes place at the ends of the stack due to expansion and contraction of gas and thus, thermoacoustic effect is observed. Heat exchangers are used to obtain the required refrigeration.
- **Heat transfer and cooling cycle**



The thermal acoustic cooling takes place in four steps: [16, 17]

- **Adiabatic Compression (1-2):**
  The gas particles move from left to right in between the stack plates due to the incoming acoustic waves. Thus, gas is compressed and pressure rises.
- **Isothermal Compression (2-3):**
  There is an increase in temperature in the compressed gas. Thus, heat transfer takes place between the hot gas and the relatively cooler stack wall. This in turn, reduces the volume of gas.
- **Adiabatic Expansion (3-4):**
  The gas particles after striking the stack wall, move back in the right direction. Thus, pressure is dropped as the gas expands again. The air temperature is reduced and the gas temperature measures lower than the plate temperature.
- **Isothermal Expansion (4-1):**
  The working gas absorbs heat from the stack wall and the expansion continues. After this stage, the temperature and pressure drop back to the initial stage of the cycle.

4. TERMINOLOGY

- Stack Length – the horizontal length of the stack used. Denoted by L_s inthis research.
- Stack Centre Position- the distance of the stack centre from the sound source. Denoted by $X_{c.}$
- Stack Spacing- the spacing in between the plates arranged in the stack. Denoted by $2Y_{o.}$
- Plate thickness- the thickness of the individual plates kept in the stack. Denoted by 2l.
- Cross sectional area- The total area covered by the stack in the resonator. Denoted by A.
- Speed of sound- the speed of sound in the resonator. Denoted by a.
- Dynamic viscosity- it is the internal resistance to flow in a fluid. Denoted by μ.

Factors affecting the efficiency:

- Working Fluid- high ratio of specific heat [8] and low Prandtl number [7]. The thermal conductivity and sound velocity should be high.
- Average pressure- Power Density is directly proportional to Average pressure. Higher the pressure, lower is the thermal penetration depth. [18]
- High pressure is also inversely proportional to the square of average pressure.
- Frequency- the thermal penetration depth is inversely proportional to the square of frequency of sound wave. Power density is directly proportional to the resonance [8] frequency. A decrease in the sound frequency means that the length of the resonance [9] tube us long.
- Drive Ratio- ideally, Mach number[10] should be less than 0.1 and the Reynolds number [11]should be less than 500.[22]

- Stack- the material used as stack should have lower thermal conductivity and high heat capacity.[19]
- When we increase the cooling load, more heat is pumped at the hot end of the stack which results in higher temperature difference.[20]
- Length of resonator- when we increase the length of the resonator, more cooling is achieved. when we decrease the resonator length, pressure oscillations increases and resonant frequency decreases. [12,21]

Equations to be used:
EnthalpyFlux,

$$H_n = -\frac{1}{8\gamma}\delta_{kn}(DR)^2\frac{\sin(2X_{cn})}{(1+Pr)\wedge}\left[\Gamma\frac{1+\sqrt{Pr}+Pr}{1+\sqrt{Pr}} - \left(1+\sqrt{Pr}-\delta_{vn}\right)\right] \quad (13)$$

Work Flux, $W_n =$

$$\frac{1}{4\gamma}\delta_{kn}(DR)^2 L_{sn}\left[BR(\gamma-1)cos^2(X_{cn})\left\{\frac{\Gamma}{(1+\sqrt{Pr}\wedge)} - 1\right\} - \frac{\sqrt{Pr}sin^2(X_{cn})}{BR\wedge}\right] \quad (13)$$

where,

$$\Gamma = \frac{\nabla T_m}{\nabla T_{cr}} = \frac{\Delta T_{mn\, tan(X_{cn})}}{BR(\gamma-1)L_{sn}} \quad (13)$$

$$\wedge = 1 - \delta_{kn\sqrt{Pr}+\frac{1}{2}+Pr\delta_{kn}}{}^2 \quad (13)$$

Drive ratio: $DR = p1/pm$
Normalized enthalpy flux: $\dot{H}_n = \dot{H}/(pmaA)$
Normalized work flux: $\dot{W}_n = \dot{W}/(pmaA)$
Normalized temperature difference: $\Delta T_{mn} = \Delta T_m/T_m$
Normalized thermal penetration depth: $\delta_{kn} = \delta_k/y_0$
Normalized vicious penetration depth: $\delta_{vn} = \delta_v/y_0$
Normalized stack length: $L_{sn} = kL_s$
Normalized stack position: $x_{cn} = k_{xc}$
Blockage ratio (porosity): $BR = y_0/(y_0 + l)$ (13)

Setup 1:

- Working Fluid = Helium-Xenon
- Average pressure = 8bar
- Frequency = 300,400,500Hz
- Drive ratio = 0.01
- Stack = mylar parallel sheet

Setup 2:

- Working Fluid = Helium
- Average pressure = 3bar
- Frequency = 250,350,450Hz
- Drive ratio = 0.02
- Stack = mylar parallel sheet

Setup 3:

- Working Fluid = Helium
- Average pressure = 2bar
- Frequency = 200,300,400Hz
- Drive ratio = 0.01
- Stack = cordierite honeycomb ceramic stack.

Setup 4:

- Working Fluid = Helium
- Average pressure = 5bar
- Frequency = 200,250,300Hz
- Drive ratio = 0.01
- Stack = Polyester Tape (PET tape)

Four different setups are made and after calculations, the most appropriate setup will be used in order to get build a TAR of good efficiency. It is to be noted that simulation software like DeltaEC[14] and MATLAB[15] are to be used to get the results.

5. CONCLUSION

We have studied the design considerations and the basic principle on which a Thermoacoustic Refrigerator works. We studied key factors which effect the performance of a TAR and hence narrowed down some set ups which can be studied and experimented to discover which one works best for a TAR.

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