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Design & Application of Standing Wave Refrigerator : An Overview

Manash Dey[1], Rishav Kumar, [2] Priya Saloni[3], Shubhankar Rao[4], Pradyuman Kumar[5], Mudit Sharma[6]

[1,6]Assistant Professor, Deptt. of Mechanical Engineering, JIMS Engineering Management Technical Campus, Greater Noida, Uttar Pradesh-201308.

[2, 3, 4, 5] UG Student, Deptt. of Mechanical Engineering, JIMS Engineering Management Technical Campus, Greater Noida, Uttar Pradesh-201308.

Corresponding Author:- Manash Dey
Mail Id:-manashdey.gn@jagannath.org

Abstract:

In an early 19th century, Modern refrigeration techniques were introduced to the world. In the last few decades the improvisation in refrigeration technologies is very much remarkable and advanced. This paper is basically focused on the implementation of thermo Acoustic refrigerator so that we can implement a better version of the refrigerator with a higher efficiency and better coefficient of performance. For the safety of the environment we need to avoid the usage hazardous gases like CFC, HCF i.e. the freons.

This paper describes the variation in performance of the Thermo Acoustic Refrigerator by altering the parameters of the refrigeration system. The parameters of the thermo-acoustic refrigeration system are Stack Material, Average Pressure, Temperature and Drive Ratio. By altering these parameters we can analyze the performance of the refrigerator.

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

Introduction:

Refrigeration is a process of cooling the surrounding and keeping its temperature lower than it's surrounding. Keeping the environment in mind, this new technology is under study as it is one of the most promising area of research. A Thermo-Acoustic Refrigerator uses sound to provide the cooling power. Sound travels is 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 Thermo-Acoustic Refrigerator. Heat Exchangers are kept at the either ends of the stack and thus the required cooling/heating is obtained.

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, Iksan setiawan(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 Parameters of Thermal Acoustic Refrigerator:

The parameters of Thermo-Acoustic Refrigerator are as follows:

- Material Parameters - Working fluid, Stack material.
- Design Fabrication - Mean Pressure, Frequency.
- Geometrical Parameters - Stack Length, Plate Thickness.

Construction:

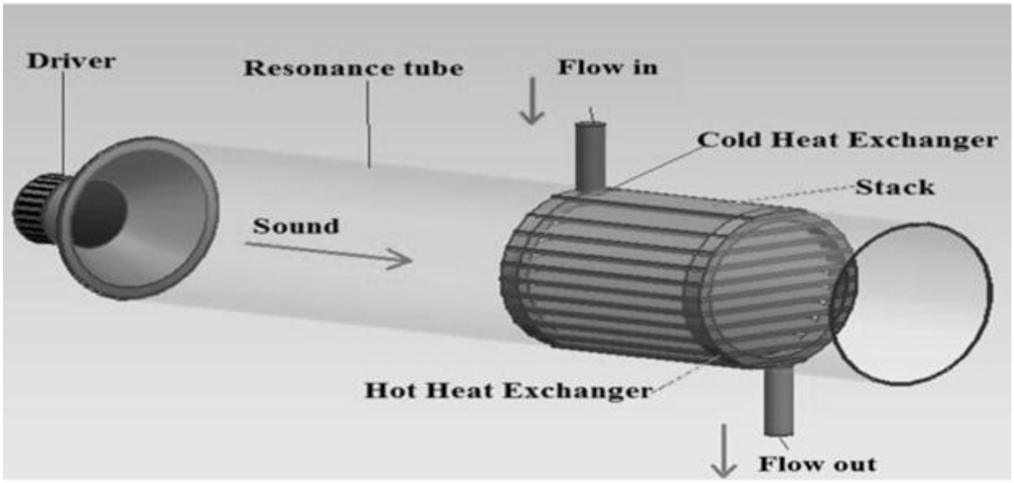
Thermo-Acoustic Refrigeration Systemconsist of a drive attached to an acoustic resonator which actually looks like a tube filled with an inert gas. In the resonator, a stack consisting of a number of parallel plates and two heat exchangers are installed. Thedriver sustains acoustic standing waves in the gas at the fundamental resonance frequency of the resonator. The acoustic standing wave displaces the gas in the channels of the stack while compressing and expanding respectively leading to heating and cooling of the gas. The gas, which is cooled due to expansion absorbs heat from the cold side of the stack and as it subsequently heats up due to compression while moving to the hot side, rejects the heat to the stack. Thus the thermal interaction between the oscillating gas and the surface of the stack generates an acoustic heat pumping action from the cold side to the hot side. The heat exchangers exchange heat with the surroundings, at the cold and hot sides of the stack.The heat exchangers are used so that heat interaction with the surrounding takes place. Heat is pumped from the cold end heat exchanger to the hot end heat exchanger.

Setup Components:

- **Driver** – The Driver of a Thermo-acoustic refrigerator is responsible for creating sound waves of high intensity. It converts the electrical power to the acoustic power. It is attached to the resonator 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.

- **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 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 Thermo-acoustic refrigerator.
- **Working Fluid** – The working fluid is filled inside the resonator. Noble gases are generally preferred as the working fluid in Thermo-acoustic refrigerator. It is important to select lighter gases over the heavier gases, which have higher sound velocity and have lower Prandtl number.
- **Temperature sensors** – These devices are used to determine the temperature during the experiment.



Terminology:

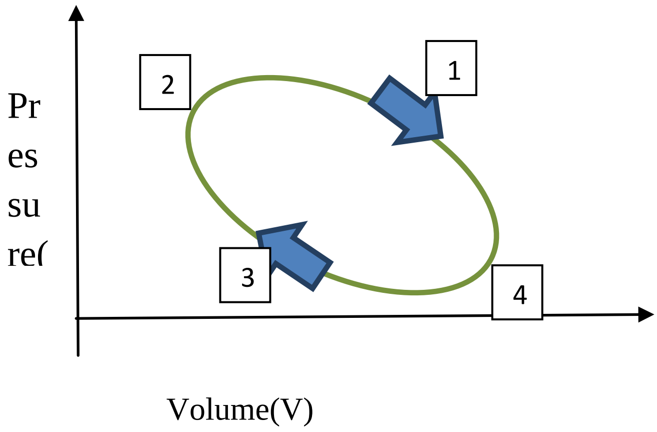
- **Stack Length** – the horizontal length of the stack used. Denoted by Ls in this research.
- **Stack Centre Position** - the distance of the stack centre from the sound source. Denoted by Xc.
- **Stack Spacing** - the spacing in between the plates arranged in the stack. Denoted by 2Yo.
- **Plate thickness** - 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.

Theory:

1. **Thermal Acoustic Effect:-**

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.

2. Heat Transfer and Cooling Cycle:-



The thermal acoustic cooling takes place in four steps:

- **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.

Factors affecting the efficiency:

- **Working Fluid** - High ratio of specific heat and low Prandtl number. 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.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 frequency. A decrease in the sound frequency means that the length of the resonance tube us long.
- **Drive Ratio**- Ideally, Mach number should be less than 0.1 and the Reynolds number should be less than 500.
- **Stack-** the material used as stack should have lower thermal conductivity and high heat capacity.When we increase the cooling load, more heat is pumped at the hot end of the stack which results in higher temperature difference.
- **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.

Equations:

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

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

Where, $\boldsymbol{\Gamma = \frac{\nabla T_m}{\nabla T_{cr}} = \frac{\Delta T_{mn\,\tan(X_{cn})}}{BR(\gamma-1)L_{sn}}}$ **and** $\boldsymbol{\wedge = 1 - \delta_{kn\sqrt{Pr}+\frac{1}{2}+Pr\delta_{kn}}^{\ \ 2}}$

Drive ratio: DR = p1⁄pm

Normalized enthalpy flux: Ḣn = Ḣ ⁄ (pmaA)

Normalized work flux: Ẇn = Ẇ ⁄ (pmaA)

Normalized temperature difference: ΔTmn = ΔTm ⁄ Tm

Normalized thermal penetration depth: δkn = δk /y0

Normalized vicious penetration depth: δvn = δv /y0

Normalized stack length: Lsn = kLs

Normalized stack position: xcn = kxc

Blockage ratio (porosity): BR = y0⁄ (y0 + l)

Setups:

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)

Conclusion:

The four setups suggested in this paper are suggested on the basis of calculations, so that the efficiency of the thermoacoustic refrigerator is increased and we have increased it’s efficiency. We used softwares like MATLAB and DeltaEC for the simulation and to get the results.

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