A Review on Thermoacoustic Refrigeration System

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***Abstract*- Thermoacoustic refrigeration is an emerging ‘green’ technology based upon the purposeful use of high-pressure sound waves to provide cooling. The design and functionality of thermo-acoustic refrigerator have been the focus of considerable attention from the research community since 1980. This environmental friendly technology has the potential to replace conventional refrigerator once the improvements in design and technology are realized.**

Index terms- Thermoacoustic, Stack, Temperature gradient

I. INTRODUCTION

Cooling devices utilizing the thermoacoustic effect have been attracting attention in view of their high reliability and other advantages due to fewer moving parts in comparison with cooling devices using compressors, etc. In addition, recently, they have been receiving attention from an environmental perspective as cooling devices that permit waste heat utilization and don’t use chlorofluorocarbon gases.

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. Thermo acoustic heat engines have the advantage of operating with inert gases and with little or no moving parts, making them highly efficient ideal candidate for environmentally-safe refrigeration with almost zero maintenance cost.

II. THERMOACOUSTIC PHENOMENON

The field of thermoacoustics is based upon the principle that sound waves are pressure waves. Sound waves are propagated through the air by the means of molecular collisions. These collisions create disturbances in air, resulting in constructive and destructive interference. Constructive interference creates a front of high pressure, compressing molecules, while destructive interference lowers pressure and in turn allows molecules in the air to expand. This property of sound waves is the foundation of the science behind thermoacoustic refrigerator.

Thermoacoustic refrigeration uses high amplitude sounds to pump heat to respective areas within the device through pressure oscillations. The wave in the thermoacoustic engine has a great amount of pressure and velocity fluctuations through the stack that the heat is given to the oscillating gas at high pressure and removed at low pressure. When it comes to the thermoacoustic pumps, the process is reversed.

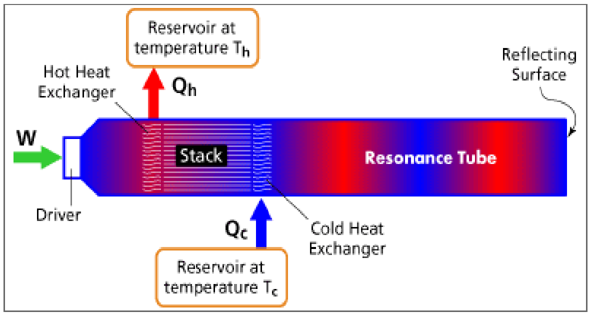

Fig.1Schematic diagram of thermoacoustic refrigeration device

One of the important fundamental sciences behind thermoacoustic refrigerator is thermodynamics, in specific the study of heat transfer. The ideal gas law states that,

$$PV= \rho RT$$

Where, P, ρ, and T are the pressure, density, and temperature of the gas, respectively, and the R is the gas constant (for air R = 287 J/kg·K). This law states that changes in gas pressure is directly proportional to changes in temperature, as the pressure of gas increases, the gas temperature also increases.

III. ENVIRONMENTAL AFFABILITY

No environmentally hazardous refrigerants are needed and only inert gases that are environmentally safe and suitable are used. The international restriction on the use of CFC (chlorofluorocarbon) and skepticism over the replacements of CFC, gives thermo acoustic devices a considerable advantage over traditional refrigerators. The gases used in these devices are (e.g. helium, xenon, air) harmless to the ozone and have no greenhouse effect. It is expected that in the near future, regulations will be tougher on the greenhouse gases. The awareness about the destructive effects of CFC on the depletion and the banning of the CFCs production, lead the researchers to find an alternative solution to this problem. In this scenario, thermo acoustic refrigerator could be the most suitable candidate to replace the conventional vapour-compression refrigeration systems. In addition, the thermal acoustic cycle also lends itself well to a more efficient proportional control rather than the primitive binary control that conventional refrigerators currently employ. All of these reasons make thermo acoustic refrigerator potentially attractive for widespread use.

IV. SOUND WAVES AND PRESSURE

Thermoacoustics is dependent upon the fact that sound waves are pressure waves and are therefore able to create pressure gradients. Normally, waves do not reflect uniformly, resulting in constantly shifting gradients. However, in a thermoacoustic device the sound waves are reflected in such a way as that they become standing waves, or waves that are self sustaining and consistent. This creates a pattern of points within the device with alternating pressure maximums and velocities, as shown in Figure 2.

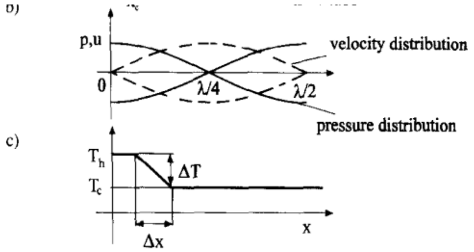

Fig. 2 Graphs of sound waves. Note the relationship between pressure and velocity – as one is at its maximum, the other is at its minimum.

Although there is no net propagation of energy in standing waves, a device such as our thermoacoustic refrigerator can be constructed to take advantage of the pressure gradients. By using acoustic resonance and a stack to regulate the heat flow of the air particles, the closed tube can create regions of hot and cold in the manner of a heat pump. Acoustic resonance occurs when the frequency of a medium's oscillations reaches that of its resonance frequency, or the point at which it vibrates naturally. At this frequency, the medium is able to absorb more energy. An added benefit is that the medium will also filter out all other frequencies, making its effect more pronounced. In a closed tube, the resonant frequency is defined as,

$$f = \frac{nV}{4L}$$

where, V and L are the volume and length of the cylinder, respectively. At the point of resonant frequency, waves oscillating in the tube are at their maximum energy; by vibrating the tube at this frequency, the optimal energy flow is attained and thus the maximum heat transfer rate. To calculate this frequency, the speed of sound at a temperature T,

$$V = 331.3\sqrt{1 + \frac{T}{273.15}}$$

and the length L of the closed tube, and harmonic n (1 for this case), are used in the equation above.

V. BASIC COMPONENTS

1. Acoustic driver: A thermo acoustic cooling device requires an acoustic driver attached to one end of the resonator, in order to create an acoustic standing wave in the gas at the fundamental resonant frequency of the resonator. The acoustic driver converts electric power to the acoustic power. From literature review, a loudspeaker with the maximum power of 15 watts at the operating frequency (400 Hz) was used as the acoustic driver. The loudspeaker was driven by a function generator and power amplifier to provide the required power to excite the working fluid inside the resonator. Efficiency of this type of loudspeaker is relatively low, and their impedances are poorly matched to gas when the

pressure inside the resonator is high. Consequently the range of pressure amplitude inside the resonator is limited.

2. Resonator tube: The resonator tube was built from a straight acrylic tube of length 70 cm. The internal diameter of the tube was 6.3 cm and the wall thickness was 6 mm. One end of the tube has a plate attached to install the speaker frame. In the present design the resonance frequency of the resonator is 400 Hz. The resonator was sealed at both ends with the rubber O-rings to minimize the sound energy leakage.

3. Stack: The most important component of a thermoacoustic device is the stack inside which, the thermoacoustic phenomenon occurs. Thus, the characteristics of the stack have a significant impact on the performance of the thermoacoustic device. The stack material should have good heat capacity but low thermal conductivity. The low thermal conductivity for the stack material is necessary to obtain high temperature gradient across the stack and a heat capacity larger than the heat capacity of the working fluid. In addition, the stack material should minimize the effects of viscous dissipation of the acoustic power.

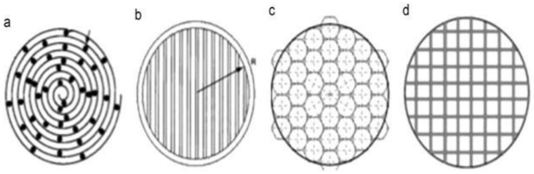

Fig 3 (a) Spiral, (b) Parallel, (c) Honeycomb, (d) Pin array

4. Heat exchangers: Heat exchangers are necessary to transfer the heat of the thermoacoustic cooling process. The design of the heat exchangers is a critical task in thermoacoustics. Little is known about heat transfer in oscillatory flow with zero mean velocity. The standard steady-flow design methodology for heat exchangers cannot be applied directly. Furthermore, an understanding of the complex flow patterns at the ends of the stack is also necessary for the design. Nowadays some research groups are using visualization techniques to study these flow patterns which are very complicated.

- Cold heat exchanger: The whole resonator part on the right of the stack in, cools down so a cold heat exchanger is necessary for a good thermal contact between the cold side of the stack and the small tube resonator. An electrical heater is placed at the cold heat exchanger to measure cooling power. The length of the heat exchanger is determined by the distance over which heat is transferred by gas. Acoustic power is also dissipated in the cold heat exchanger.
- Hot heat exchanger: The hot heat exchanger is necessary to remove the heat pumped by the stack and to reject it to the circulating cooling water. As discussed in the precedent section, the optimal length of the heat exchanger is equal to the peak-to-peak displacement amplitude of the gas at the heat exchanger location. But since the hot heat exchanger has to reject nearly twice the heat supplied by the cold heat exchanger, the length of the hot heat exchanger should be twice that of the cold heat exchanger.

4. Working fluid: Many parameters such as power, efficiency, and convenience are involved in the selection of the working fluid, and it depends on the application and objective of the device. Thermo acoustic power increases with an increase in the velocity of sound in the working fluid. The lighter gases such as He, Ne have the higher sound velocity. Lighter gases are necessary for refrigeration application because heavier gases condense or freeze at a lower temperature, or exhibit not ideal behavior.

5. Thermocouple: J-type thermocouples are used for the temperature measurements in this study. They are used to measure the temperature at different locations inside the resonator and the temperature of heat exchanger fluids. The specifications of the thermocouple are given below:

- Thermocouple grade :- 0 to 150 ℃
- Limits of Error:-1.0 ℃ or 0.75% above 0℃.

VI. DESIGN ASPECTS

The stack is considered as the heart of any thermo acoustic system. It can be seen that these systems have very complicated expressions which cannot be solved, which necessitates the use of approximations. The coefficient of performance of the stack for example which can be defined as the ratio of heat pumped by the stack to the acoustic power dissipated in the stack. A simplified expression is derived from the short stack and boundary–layer approximation. However, even after the approximation, the expression looks complicated. They contain a large number of parameters such as working gas, material and geometrical parameters of the stack. It is difficult to deal with so many parameters in engineering. However, one can reduce the number of parameters by choosing a group of dimensionless independent variables. Some dimensionless parameters can be deduced directly. Others can be defined from the boundary layer and short stack assumptions.

Table 1 Operation-, working gas-, and stack parameters.

Operating parameters	Working gas parameters
Operating frequency, f	Dynamic viscosity, μ
Average pressure, Pm	Thermal conductivity, K
Mean temperature, Tm	Sound velocity, a
Drive ratio, $\frac{Po}{Pm}$	Ratio of specific heats, γ

Stack material	Stack geometry
Thermal conductivity, Ks	Length, Ls
Density, ρs	Stack center position,Xs
Specific heat, Cs	Plate thickness, $2l$
	Plate spacing, $2yo$
	Cross section, A

1. Stack Design

The boundary-layer and short-stack approximations assume the following:

• The reduced acoustic wavelength is larger than the stack length$\frac{\lambda}{2\pi} \geq Ls$; so that the pressure and velocity can be considered as constant over the stack and that the acoustic field is not significantly disturbed by the presence of the stack.

- The thermal and viscous penetration depths are smaller than the spacing in the stack: $\delta k, \delta v \leq y$ This assumption leads to the simplification of Rott’s functions, where the complex hyperbolic tangents can be set equal to one.
- The temperature difference is smaller than the average temperature: $\Delta Tm \leq Tm$, so that the thermo physical properties of the gas can be considered as constant within the stack.

The length and position of the stack can be normalized by$\lambda/2\pi$. The thermal and viscous penetration depths can be normalized by the half spacing in the stack$y0$. The cold temperature or the temperature difference can be normalized by Tm. Since δk and δv (see below) are related by the Prandtl number σ, this will further simplify the number of parameters. Olson and Swift proposed to normalize the acoustic power W and the cooling power Qc by the product of the mean pressure Pm ; the sound velocity a, and the cross-sectional area of the stack A: $Pm * a * A$. The amplitude of the dynamic pressure can be normalized by the mean pressure. The ratio $\frac{Po}{Pm}$ is called the drive ratio D. In practice the stack material can be chosen so that the thermal conductive term in the heat flow expression can be neglected. In this case the parameters of the stack material do not have to be considered in the performance calculations. The porosity of the stack, sometimes called blockage ratio and defined as,

$$B = \frac{yo}{yo + l}$$

is also used as a dimensionless parameter for the geometry of the stack. The thermal and viscous penetration depths are given by

$$\delta k = \sqrt{\frac{2K}{\rho\, Cp\, \omega}}$$

And,

$$\delta v = \sqrt{\frac{2\mu}{\rho\omega}}$$

Where, K is the thermal conductivity, μ is the viscosity, ρ is the density, Cp is the isobaric specific heat of the gas, and ω is the angular frequency of the sound wave.

2. Stack material: The heat conduction through the stack material and gas in the stack region has a negative effect on the performance of the refrigerator. The stack material must have a low thermal conductivity Ks and a heat capacity Cs larger than the heat capacity of the working gas, in order that the temperature of the stack plates is steady. The material Mylar is chosen, as it has a low heat conductivity (0.16 W/m K) and is produced in many thicknesses between 10 and 500 µm.

3. Working gas: Helium is used as working gas. The reason for this choice is that helium has the highest sound velocity and thermal conductivity of all inert gases. Furthermore, helium is cheap in comparison with the other noble gases. A high thermal conductivity is wise since δk is proportional to the

square root of the thermal conductivity coefficient K. The effect of using other gases is discussed elsewhere.

4. 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, A resonance frequency of 400 Hz is used.

5. Average pressure: Since the power density in a thermoacoustic device is proportional to the average pressurePm, 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 results 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 (see below), the maximal pressure is 12 bar. Average pressure of 10 bar is used.

6. Dynamic pressure: The dynamic pressure amplitude Po is limited by two factors namely, the maximum force of the driver and non-linearity. The acoustic Mach number, defined as

$$M = \frac{Po}{Pm * a^2}$$

has to be limited to $M \approx 0.1$ for gases in order to avoid nonlinear effects. From many experimental studies on the structure of turbulent oscillatory flows, it has unanimously been observed that transition to turbulence in the boundary layer took place at a Reynolds number (Ry) based on Stokes boundary-layer thickness, of about 500– 550, independent of the particular flow geometry (pipe, channel, oscillating plate). Since it was intended to design a refrigerator with moderate cooling power. Driving ratios D < 3% is used, so that $M < 0.1$ and $Ry < 500$:

7. Thermal Penetration Depth: One critical variable in the construction of the thermoacoustic device was the spacing between the layers of the stack. This distance is critical because it directly affects the efficiency of the device. If the space is too small, air cannot transfer the sound waves, which causes the stack to behave as a stopper. However, if the spacing is too wide, then too little air gets in contact with the stack, and not enough heat is transferred. The distance between these extremes that is most effective is described by G.W. Swift as 4 thermal penetration depths. A thermal penetration depth is the distance heat travels through air in one second. The optimal distance is four times that distance. Unfortunately, due to limited materials, it was restricted to a stack which included spacing of only 2.5 penetration depths. When human error is factored into stack creation, however, It was unable to completely compact the stack hence it was reasonably close to the optimum 4 depths.

Table 2 Normalized Design Parameters

The resultant normalized parameters are given an extra index n and are shown in Table 2. The number of parameters can once more be reduced, by making a choice of some operation parameters, and the working gas.

Non dimensional parameters
Normalised thermal penetration depth, δkn
Normalised stack center position, Xsn
Normalised stack length, Lsn
Normalised acoustic power loss in small diameter resonator tube, $\frac{W2}{n}$
Acoustic mach number, M

VII. EXPERIMENTAL SETUP

Fig.4 Experimental setup of Thermoacoustic refrigeration system

VIII. RESULTS & ANALYSIS

The results have shown that the performance of the refrigerator depends on the working gas, pressure inside the resonator tube, shape of the resonator tube, material, position and length of the stack. Another merit of this device is that it could provide cooling and heating simultaneously, that is cooling from the cold-end and heating from the hot-end. The following results we get from experimental study:

- Without the stack the temperature along the resonator tube is almost constant the variation is within 0.5℃.
- Temperature distribution along the resonator is significant effected by the presence of stack. After nearly 18 minutes of operation a temperature gradient of 7 ℃ was established across the stack.
- The position of the stack is important in order to get maximum temperature gradient across the stack.
- The power input is important to get the maximum temperature gradient across the stack; therefore an efficient acoustic driver is very important to get better COP.

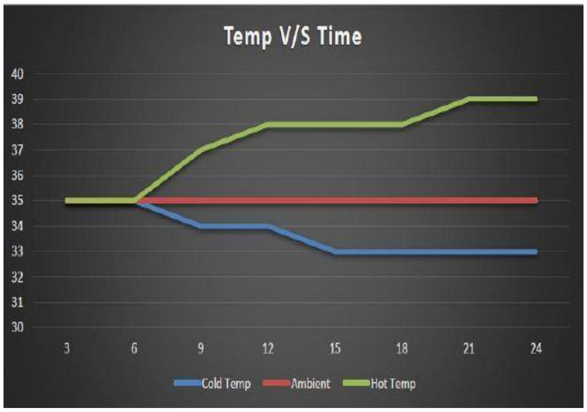

Fig.5 Temperature VS Time history of thermoacoustic refrigeration system

IX. CONCLUSION

Thermoacoustic refrigeration is an innovative alternative for cooling that is both clean and inexpensive. The refrigeration effect is achieved by using sound waves and inert gas which will not cause any damage to the atmosphere (i.e. Eco-friendly). Their benefits compared with their vapor-compression counterparts and simplicity, they are currently still less efficient (COP < 1) than traditional vapor-compression refrigerators.

Thermoacoustic refrigeration also has a broad range of applications, including computers and nanotechnology. It will likely be employed by the military and space program, due to its low-maintenance, toxic-free, high-reliability cooling methods. Thermoacoustic engines and refrigerators were already being considered for a few years ago for specialized applications, where their simplicity, lack of lubrication and sliding seals, and their use of environmentally harmless working fluids were adequate compensation for their lower efficiencies.

In future let us these thermoacoustic devices help to protect the planet might soon take over other costly, less durable and polluting engines and pumps.

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