Thermoacoustic Refrigerator: A Review on Design, Fabrication and Performance

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Abstract: *With the onset of climate change, many researchers are seeking out new ways to reduce the harmful effects of existing machines. Much of the recent research and development pursuits are concerned with the performance of conventional refrigeration process, specifically to reduce the emission of harmful gases and to seek a new reliable refrigeration processes. A Thermoacoustic Refrigerator (TAR) makes use of a refrigeration process that converts acoustic energy to heat energy. It is an eco-friendly refrigeration process that employs inert gases instead of CFCs and HCFCs which does not have any moving components. This paper reviews the concept of a thermoacoustic refrigerator, its working principle, different optimization techniques to enhance Coefficient of Performance (COP) along with the investigation of its constituent parts and parameters.*

Key words - conventional refrigeration, thermoacoustic refrigerator, stack, inert gases.

I. INTRODUCTION

The International Institute of Refrigeration (IIR) estimates that the total number of refrigeration, air-conditioning, and heat pump systems in operation worldwide is roughly three billion. Global annual sales of such equipment amounts to roughly 300 billion USD. Almost 12 million people are employed internationally in the refrigeration sector which consumes about 17% of the overall electricity used worldwide. [1] Thus, it becomes necessary to find economically viable solutions to meet these demands while keeping in mind the protection of the environment for the future generations. The aspects to be tackled are a reduction in greenhouse gas emissions and better ozone layer protection. For some time now, because of their harmful effect on the environment, the use of halogenated refrigerants has been greatly subjected to scrutiny. The introduction of thermoacoustic into the field of refrigeration can bring down the cost of refrigeration while also reducing the destruction to the environment. Thermacoustic refrigeration is a viable alternative for refrigeration that is relatively cleaner and more economical. Refrigeration comprises two major thermodynamic principles. Firstly, the coolant’s temperature rises during its compression and drops during expansion. Secondly, the Clausius’s statement states that without external input, when any two substances kept in direct contact, the flow of heat will always be from the hotter substance to the colder one. Conventional refrigerators rely on pumps for the transfer of heat. Thermoacoustic refrigerators, however, use sound for the generation of pressure waves which cyclically compress and relax the gas particles within the tube to produce the cooling effect. Such systems use no adverse chemicals and are also capable of utilizing the heat lost from the gas in an energy system to provide the necessary acoustic power. Thermoacoustic is the study of the conversion of sound energy to heat energy and vice versa. It is based on the principle that sound waves are pressure waves. These sound waves propagate through the air via molecular collisions. The molecular collisions cause a disturbance in the air, which in turn creates constructive and destructive interference. The constructive interference heats the molecules during compression, and the destructive interference makes the molecules expand while cooling the gas parcel. This is the principle behind thermoacoustic refrigerator. Even though the efficiency of thermoacoustic devices is lower than that of conventional refrigerators, they have lots of other positive factors over the latter. Some of the factors are low cost, high reliability and more eco-friendliness.

II. METHODOLOGY

The figure below shows the methodology of the thermoacoustic phenomenon in a stack. The motion of the acoustic wave causes a parcel of gas inside the stack to start moving towards the left i.e. towards the end of the buffer volume. During this motion there is an increase in pressure and this causes the compression of the gas parcel. Due to this gas parcel’s higher temperature, it expands the excess heat to the cooler stack walls. This causes the gas parcel to shrink. As the working cycle proceeds, the gas parcel is drawn back towards the acoustic driver side, where there is lower pressure. Further, the gas parcel, now less dense than its surrounding medium, is also cooler than its adjacent stack walls. This facilitates absorption of heat from the stack walls, which in turn causes the parcel to expand. This cycle repeats and when considerable number of particles flow past the stack walls, a substantial heat transfer occurs from one end to the other. [2]

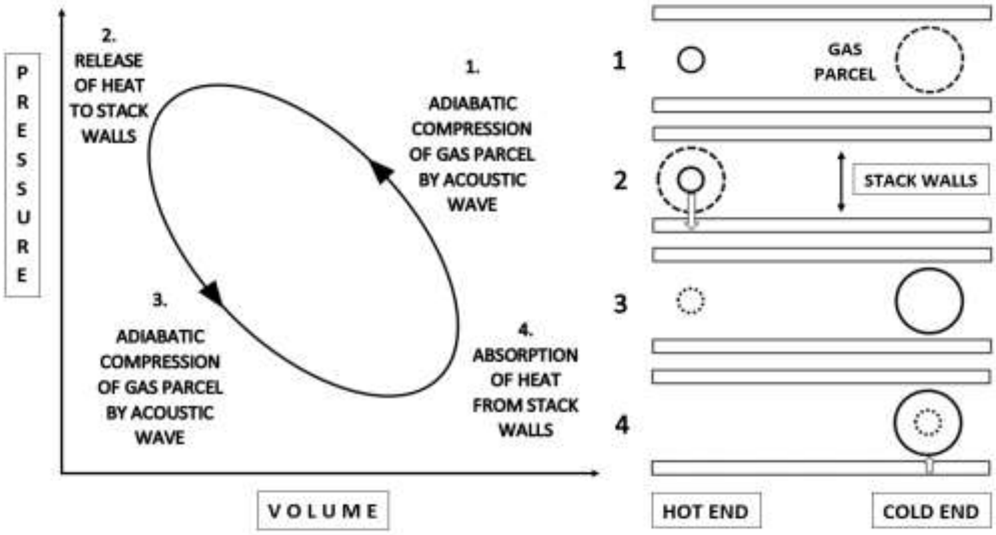

Fig.1. Working of thermoacoustic refrigerator

III. GENERAL EXPERIMENTAL SETUP

A standing wave thermoacoustic refrigerator consists of an acoustic driver (generally an electro-dynamic speaker adapted for a particular cooling load) along with its housing, attached to a resonator tube, filled with the working medium. The heart of the thermoacoustic refrigerator i.e. the stack, is placed within this resonator. Additionally, two heat exchangers are placed across the stack to make the apparatus suitable for practical applications. The construction of the system is such that easy replacement of specific parts is possible. This facilitates optimization of individual parts instead of the whole setup. The resonator will respond with a standing wave only if the acoustic driver delivers the appropriate frequency input. This will further amplify the input from the driver. The standing wave drives a thermoacoustic process within the stack. The stack is the name given for the core of a thermoacoustic refrigerator and is placed inside the resonator between a velocity antinode and pressure antinode of the sound wave. The heat accumulated is pushed towards the pressure antinode based on the thermoacoustic process [3].The manufacturing process of a thermoacoustic refrigerator, construction of its different parts has been explained by M.E.H Tijani et al.[4] A low temperature of -65 C was realized. The device was used to study the effects of various thermoacoustic parameters, such as Prandtl number, stack spacing etc. Ramesh Nayak and et al. [5] conducted experiments for performance evaluation of thermoacoustic refrigerator subjected to various operating condition such as frequency, mean pressure, stack geometry, input power and heating load. It was designed for a cooling power of 10W using pure Helium and compressed air as the working medium. The entire resonator system was constructed from aluminum. The inner surface of the resonator tube was coated with polyurethane material to reduce heat loss from conduction. They considered stack made up of Mylar sheets having parallel plates and stack made up of Epoxy glass having holes of 1mm, 2mm and 3mm diameters for the purpose of comparing the results. Their research work they have showed that COP of the refrigerator increases with increase of heating load and decreases at higher acoustic power. The temperature difference between hot end and cold end of the stack is higher at 2W heating load and lower at 10W heating load for operating frequency 400 Hz. The temperature difference across the hot end and cold end of the stack increases with the increase of acoustic power for a mean pressure of 10 bar.

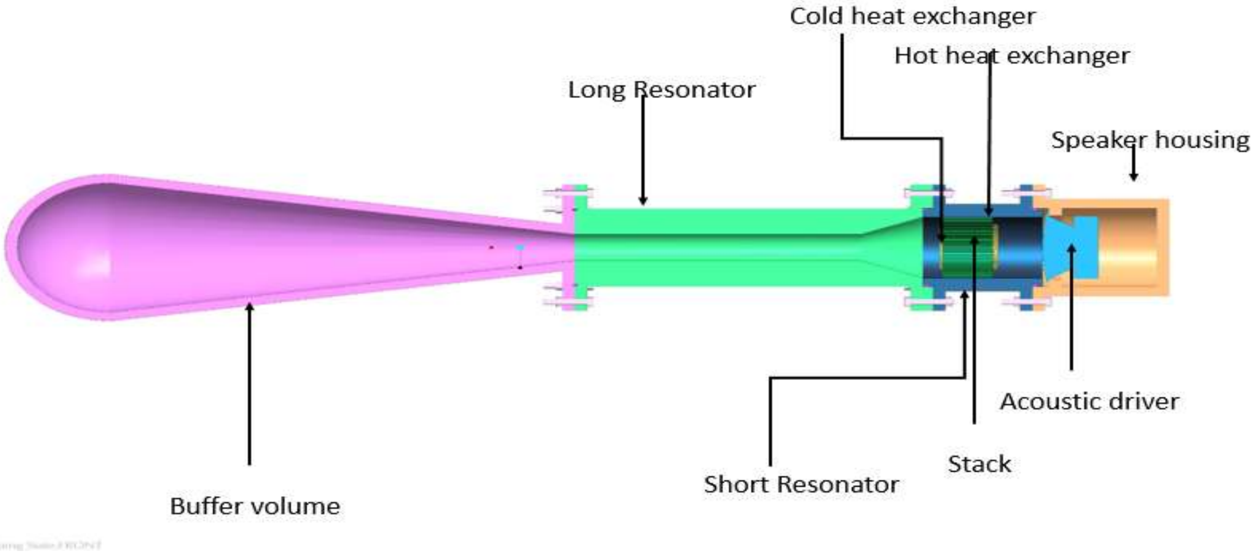

Fig.2. Experimental setup of thermoacoustic refrigerator

Sreenesh Valiyandi [6] worked on design and fabrication of thermo-acoustic refrigeration system. This device consisted of an acoustic driver attached to an acoustic resonator (glass tube) filled with air as working fluid and inside the resonator tube, a stack (Aluminium foil) of thin parallel plate is installed for the heat transfer. He analyzed the performance of thermos-acoustic refrigeration system and got a temperature difference of 3˚C in 90 minutes between the two ends of the stack. He stated that if one can able to build the device with better materials, such as a more insulating tube, might get better results.

IV. RESONATOR, STACK AND HEAT EXCHANGER DESIGN

The stack is the most essential part of a thermoacoustic device. It is here that the heat gradient is experienced. The transfer of heat between the working fluid and the stack plate is purely conductive and occurs within a thermal penetration depth. A large heat transfer area would result in higher cooling. This is the reason, Wheatley et al. [7] proposed that the stack be made of solid walls that are 2 to 4 thermal penetration depths apart. Ishikawa et al. [8] investigated the influence of stack length when the spacing is greater than the thermal penetration depth. It was found that the energy dissipation close to the plates increased by degree of 2 with the particle displacement. There was also no heat transfer resulted when the spacing of the plate was equivalent to the thermal penetration depth. The COP of a thermoacoustic refrigeration system calculated by means of temperature variation along stack was studied by Hariharan et al. [9]. As the spacing in the stack increases, the temperature difference decreases. Hariharan observed that the initial temperature difference increases slowly and stabilizes with time. This is the result of smooth convection between the working fluid and the plate. When looking at stack geometry, the objective to achieve is to increase the surface area of the solid walls where heat transfer takes place, so that the thermoacoustic effect can occur with ease. Looking through the past geometries employed, the most frequent used are the circular hole, parallel, rectangular slab, spiral, and hexagonal types. It can be visualized as shown below. If the walls of the stack are too close or too far apart, effective heat transfer cannot take place [7]. The ease of fabricating the desired geometry also plays a huge role in the setup.

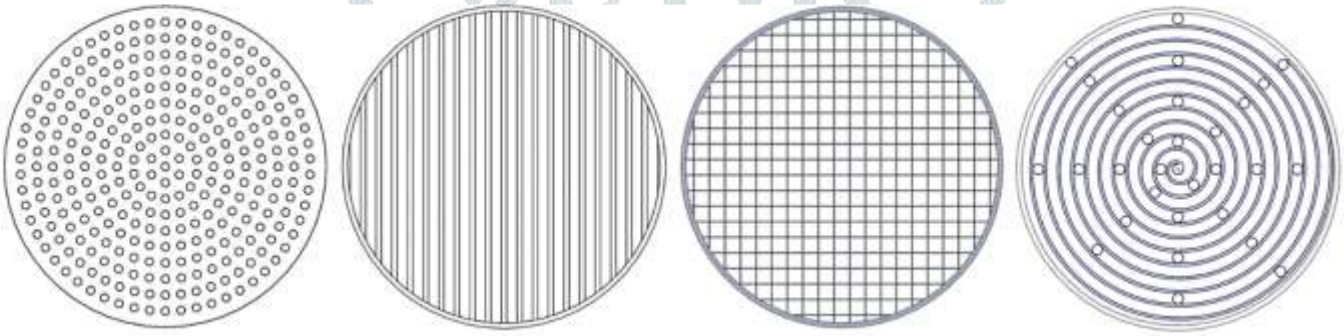

Fig.3. Geometry of different types of stack

Nor Atiqah Zolpakar et al. [10] studied the performance of a 3D-printed stack in a standing wave thermoacoustic refrigerator. they have optimized the stack design parameters selected with Multi-Objective Genetic Algorithm (MOGA) to determine the optimum design parameters; stack length, center position and plate spacing. They have measured the temperature recorded at both ends of the optimized stack center position at various stack length of 3 cm, 4 cm, and 5 cm. The maximum temperature difference with obtained with the optimized stack position at 4 cm. Based on the designed temperature difference across the stack, results have shown the superior performance obtained in terms of the higher temperature difference achievable with the 3D-printed stack compared to previous ones under the same design and operating conditions. Allesina et al. [11] illustrated that a stack in a standing wave thermoacoustic refrigerator is most effective when it has low thermal conductivity and high heat capacity. Materials like PVC, epoxy and mylar are great stack materials. Mylar is the most effective stack material as it has a very low thermal conductivity which helps in preventing diffusion of heat through stack. Yahya et al. [12] evaluated the thermal performance of a thermoacoustic refrigerator using different materials for stack. Materials like stainless steel, copper, carbon foam and Mylar were made into stacks and tested on. Their results showed that Mylar was the most effective stack material. They also showed the effect of the stack material on the performance of a thermoacoustic refrigerator ultimately depends on the viscous to thermal penetration depth ratio ($r_h/\ \delta_k$).By using air as a working fluid, Hariharan et al. [13] illustrated the effect of resonator length, thickness of plate and plate spacing on the COP of a thermoacoustic engine. Jithin George [14] investigated the effect of resonator tube length. If the length of resonator increases, it will increase the hot end temperature. Bassem et al. [15] studied the performance of an optimized refrigerator by a numeric optimization of regenerator radius and regenerator position. For different diameters of spherical element of regenerator Biwa et al. [16] showed the correlation of phase angle between pressure and displacement oscillations of working gas on refrigerating effect of a Gifford-McMahon refrigeration system. The common resonator designs that are adopted are the half-wave length and quarter wavelength resonators. Quarter wavelength resonators are effective in reducing the dissipative effects of the gas molecules situated near the inside surface of the tube. The different types of resonator tubes are shown in Fig.4.

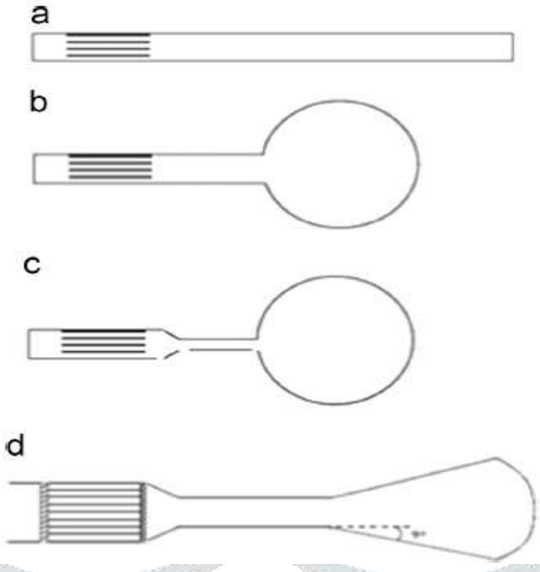

Fig.4. Different types of resonator tubes; half wavelength (a), quarter wavelength with sphere buffer volume (b), two diameter resonator with sphere buffer volume (c), and two diameter resonator with conical buffer volume.

Zolpakar et al. [17] analysed the heat transfer between the working fluid and the wall where conduction occurs. He illustrated that the area for heat transfer should be large for the cooling process to happen in huge amounts. Hence, the stack is made of multiple walls that are separated by 2-4 thermal penetration depths. If the wall of stack is too close or too far apart, effective heat transfers between the stack wall and gas packet cannot occur effectively. The works of Gaelle et al. [18] and Nsofor et al. [19] emphasized their study on the fluctuating heat flow in heat exchangers in a thermoacoustic refrigerator. The effects of Prandtl number, Reynolds number, and Nusselt number were utilized to obtain a relationship for heat transfer within the heat exchanger. It was found out that inaccuracies can result considering the correlation of transfer of heat for straight flow to design and analysis. Furthermore, the advanced mean pressures resulted in better heat transport coefficients when the refrigerator is run at significant frequencies. Mekdad et al. [20] experimented the effects of frequency, stack position, wave patterns and heat exchanger of a thermoacoustic refrigerator. His investigation on the different design parameters concluded that adding a heat exchanger facilitates the performance of a thermoacoustic device. Ishikawa et al. [21] elaborated on the sizes of hot and cold heat exchanger along with entropy generation rates in a thermoacoustic engine. The temperature differences along the regenerator stack and their location in the resonator was also explained. It was realized that the heat transfer effect is more important than the viscous effect in the decrease of the entropy generation. Adding on, the size of the cold heat exchanger should be larger than the hot heat exchanger. Paek et al. [22] conducted experiments based on linear thermoacoustic theory, in which, heat exchangers were used with and without the flow of water. It was found out that when the stack temperature contour tends to be nonlinear, the COP significantly reduces.

V. EFFECT OF WORKING FLUIDS

In thermoacoustic refrigeration, inert gases are known to be the most effective working fluid [23]. Not only are they efficient but they also have no harmful effects to the environment. The cooling power is proportional to sound velocity in gas. Higher the sound velocity, greater is the cooling power. The sound velocity in inert gases are generally high. Moreover, as the thermal conductivity of the working fluid increases, the transfer of heat between the oscillating fluid particles and the stack get easier. Hence, the thickening of the thermal penetration depth desired for cooling effects. Dynamic Pressure in a thermoacoustic refrigerator is one of the many important parameters. It is responsible for the cold temperature and the refrigerators cooling power. Dhuley et al. [24] investigated the effect of resonant frequency and charging pressure on dynamic pressure which exists in a thermoacoustic refrigerator. Mouley et al. [25] experimented on a binary gas mixture for their thermoacoustic refrigerator and obtained a result of 208K. They studied the effect of different factors, such as COP and Prandtl number on the refrigerator. Air can also be used as a working fluid as it is readily available and can be used to experiments to determine the relationship between design and operating parameters.

VI. IMPORTANCE OF ACOUSITC DRIVER, FREQUENCY AND MEAN PRESSURE

In a conventional thermo-acoustic setup, the acoustic device produces sound waves which are required to drive the whole apparatus. This acoustic device is usually a loudspeaker and is installed at one end of the setup. Tang et al. [26] illustrated the effect which different sizes of acoustic pressure amplifier had on the performance of a standing wave thermoacoustic refrigerator. Zink et al. [27] employed a state of the art speaker, which was more powerful than ordinary speakers, to obtain more acoustic power. They illustrated the effect of operating frequency on the performance of thermoacoustic refrigerator. Mekdad et al. [20] also found that using sine waves resulted in the highest temperature difference.

Pan et al. [28, 29] illustrated the effect of operating frequency on the initial temperature. A comparison between self-energized fluctuation and forced fluctuation driven through loudspeaker was experimented. It was found that compulsory fluctuation had advanced selectivity for operation frequencies. The fundamental frequency or self-energized fluctuation frequency is the best option to run a thermoacoustic system in a realistic environment. While, Trapp et al. [30] utilized a mathematical programming model to optimize the COP of thermoacoustic heat engine. The standing wave frequency employed is chosen based on the working fluid used, length of the resonator and the boundary conditions. As the power density varies linearly with the resonance frequency [31], a high resonance frequency is desired. But, the thermal penetration depth is inversely proportional to the square of the frequency. Hence, a large frequency would result in a stack with small spacing. The effect of these two parameters are thus compensated. The researchers that have been mentioned in this paper have all taken frequencies between 300Hz to 500Hz, as the mechanical acoustic frequency has to be matched with the resonator acoustic frequency. The same is applicable with mean pressure. Power density is proportional to mean pressure [31] and it is desired that a high pressure is chosen. While the limit depends on the mechanical strength of the resonator. The thermal penetration depth varies inversely with the pressure and thus a large mean pressure cannot be employed. Nsofor et al. [32] constructed a thermoacoustic refrigerator using an aluminum tube to make the resonator. A plastic lining was utilized to reduce heat losses due to conduction. It was noticed that as temperature variation among the stack ends increased, the cooling effect it generated also increased. It was realized that the system should be operated on an optimum frequency and optimum pressure in order to obtain maximum cooling load. Hence, it isn't necessary that the system worked on higher pressure in order to obtain a high cooling load. Abkar and et al. [33] reported the influence of wave patterns and frequency on thermoacoustic cooling effect. The set up was made up of acrylic tube with loudspeaker on one end and an aluminum plug milled on another to create closed end. The stack was made from a 35 mm photographic film role separated by fishing line to allow the air to move along the longitudinal axis of the acrylic tube. The experiments were conducted for a frequency range of 365-425 Hz for three wave patterns, namely sine wave, square wave and triangle wave. Each experiment was conducted at the same power and frequency level for 300 seconds and the temperature difference across the stack was measured. A maximum temperature difference of 28˚C was achieved using square wave at frequency of 405 Hz.

VII. OPTIMIZATION TECHINQUIES

It is very important to identify the optimum operating conditions for the design, fabrication, and operation of a thermo-acoustic refrigerator. Theoretical, numerical and experimental studies have been done to get the optimum operating conditions. Worlikar et al. [34] carried out simulation of a numerical model for a thermoacoustic device. He made numerically investigation of the unsteady flow and the temperature field in the vicinity of ideal thermoacoustic refrigeration system by simulation of energy equation, momentum and unsteady mass within the thin-plate and low Mach-number boundaries. The heat exchanger length and position are analyzed with the variations of COP. Tijani et al. [35] explained in detail the designing criteria for thermoacoustic refrigerator in order to achieve an optimal system based on linear thermoacoustic theory. The number of operating parameters are decreased and the equations are simplified using the dimensionless independent variables. Stack length, porosity, stack position and acoustic frequency are all variables which influence efficiency or the performance of system. The result reported give guidance on the identification of highest performance, outcome of plate spacing and geometry of plate in the stack on the performance of the device based on the coefficient of performance (COP). Similarly, Bheemsha et al. [36] explained the optimization and design of a thermoacoustic refrigeration system considering its simplified assumptions on the basis of general linear theory of thermoacoustic. Optimization was carried out using MATLAB. Ghorbanian et al. [37] developed a basic representation which allowed in investigating and identifying the most significant physical characteristics of a dense traveling wave thermoacoustic refrigeration system run via traveling wave thermoacoustic engine. The place, hydraulic radius and length of the thermoacoustic refrigerator were optimized to obtain highest overall COP along with the prime mover efficiency and dimensionless dissipation of heat. Hariharan et al. [38] with the help of Response Surface Methodology optimized parameters like stack length, stack location, acoustic frequency and stack plate spacing to design thermoacoustic refrigerator. They developed a mathematical model based on Response Surface Methodology from the results obtained through software DeltaEC (Design Environment for Low-Amplitude Thermoacoustic Energy Conversion). In the same way S. Balonji et al. [39] simulated standing wave thermo-acoustic refrigeration model using DeltaEC. The performance was evaluated in terms of relative coefficient of performance by varying the geometrical configuration (Diameter, Length and Position) of ceramic substance used as stack in TAR.

VIII. CONCLUSION

Although TAR is in its conceptual stage, many researchers have already implemented the concept in various applications. Jaworski et al [40] researched on developing a thermoacoustic device for power generation and refrigeration. This was envisioned to be used in remote and rural areas to store vital medical supplies where there is limited access to electricity. Zhanga et al [41] showed that a TAR can be effectively used for the liquefaction of natural gas. The theoretical investigation shows that the COP of a thermoacoustic refrigerator is directly dependent on the working gas and efficiency of the Stack and Heat Exchanger. However, the stack can be further optimized in the areas of material design and mechanical design. Additionally, the variations in stack geometry i.e. Honeycomb structure, wire meshes, permeable screens and so on, can also be developed further. The fluid flow inside the heat exchanger will impact on its rate and amount of heat transfer. Thus, varying the flow velocity, flow frequency, the work temperature of tube, angle, tube spacing, and tube length can help improve the performance of the heat exchanger. In conclusion, the transmission of heat from stack to heat exchanger can be enhanced to increase the performance characteristics of the TAR. Most of the research done till date have used either a constant diameter or a converging tube resonator. However, the effect of using a convergent-divergent resonator has yet to be studied thoroughly.

The use of a convergent-divergent resonator enables the velocity of the gas to be further increased. An increase in the velocity of the working medium can help reduce the required input power. The effect of various working fluids like nitrogen, argon and different gas mixtures such as helium-argon, helium krypton, and helium-xenon on cooling load is another aspect of thermoacoustic refrigeration that needs to be studied extensively.

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