International Journal of ChemTech Research
CODEN (USA): IJCRGG, ISSN: 0974-4290, ISSN(Online):2455-9555
Vol.10 No.7, pp 540-552, 2017

A Critical Review on Thermoacoustic Refrigeration and its Significance

K. Augustine Babu, P. Sherjin

Sri Ramakrishna Institute of Technology, Coimbatore-641010, Tamil Nadu, India

Abstract : Conventional refrigeration system is being used widely for cooling purposes using various chemical refrigerants currently. However, this present scenario poses a major threat to the environment as the emission of harmful gases like ChloroFluoro Carbon (CFC), Hydro ChloroFluoro Carbon (HCFC) are on the rise due to the excess use of chemicals, and the requirement for refrigeration system is increasing. Hence, there is a necessity to find an alternative to conventional refrigeration. Thermoacoustic refrigeration system is one of the harmless types of refrigeration system, which offers a wide range of scope for further research. Some key advantages include no emission of harmful ozone depleting gases as chemical refrigerants are not required and the presence of no moving parts. The major disadvantage of the method is lesser Coefficient of Performance. This field is gathering the attention of many researchers as it combines both the disciplines of thermal and acoustics. Researchers have found the influence of various parameters of the components, the working fluid, and the geometry of the resonator on the performance of the device. Simulations using software are also being developed from time to time. The main objective of this paper is to present a detailed overview on the arrangement and functioning of the refrigeration system using high intensity sound waves. A review on the works done in this area, the advancements made and the future scope are also discussed.
Keywords : Refrigeration, No refrigerants or chemicals, Acoustics, Stack, Sound waves, Cooling, Temperature Difference.

Introduction

Thermoacoustic deals with the study of the inter relationship between heat and sound. A Thermoacoustic refrigerator is an arrangement that brings out the effect of cooling by means of using high intensity sound waves. The sound waves of high intensity are regarded to be pressure pulsations. These pressure pulsations come in contact with the stack material that is placed inside a resonator tube. The sound waves travel inside the resonator tube leading to the formation of standing wave. The interaction between the original wave and the wave reflected back causes expansion and rarefaction of the sound waves. This causes the heat transfer across both the ends of the stack. By the usage of proper heat exchangers on either side of the stack, the lower temperature obtained can be used to obtain the required refrigeration effect.

Experimental Set-Up

Driver

The driver of the Thermoacoustic refrigeration system is one of the major components as it creates the sound waves of high intensity. The frequency of the sound waves to be sent into the resonator is set by means of using the function generator. After amplifying the waves in the amplifier, it is sent through the loudspeaker. The driver is connected with the resonator tube such that the sound waves from the loudspeaker at the pre-set frequency are passed into the resonator. The loudspeaker must be properly insulated to avoid any leakage of the sound waves.

Resonator

The high intensity sound waves from the loudspeaker travel through the resonator. The resonator contains the working fluid. The waves interact with the stack inside the tube, where the heating and cooling across the ends are produced. There should be minimal losses at the resonator. The resonator may be of half wavelength type and quarter wavelength type and with or without buffer volume of various geometries.

Stack

The stack is the part of the system placed inside the resonator where the thermoacoustic effect takes place. In the stack, the acoustic power is converted into heat. The amount of heat produced is predominantly dependent on the material properties of the stack such as the thermal conductivity, heat carrying capacity, the porosity and the length of the stack. The position of the stack in the resonator also decides the amount of refrigerant that can be obtained.

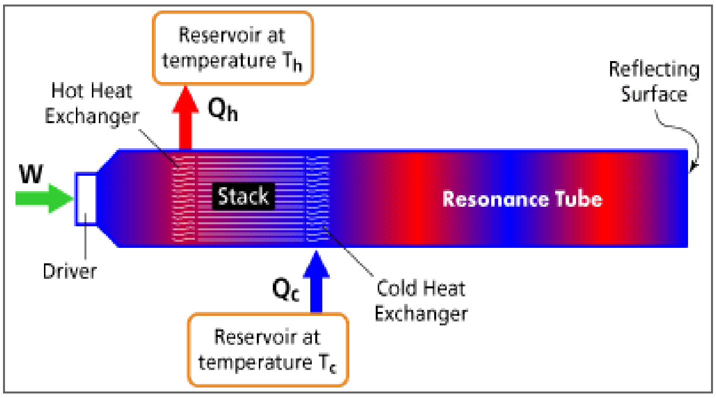

Figure 1. Layout of Thermoacoustic Refrigerator

Figure 2. Honey Comb Ceramic Stack

Heat Exchangers

Heat exchangers are placed on the stack at either ends of the stack and enable the transfer of heat produced from the stack ends. Optimal design of the stack is essential to get maximum difference in temperatures.

Working Fluid

The working fluid is filled inside the resonator. Generally, noble gases are used as the working fluid. The fluid is usually filled with high pressure. Atmospheric air can also be used as the working fluid.

Methodology

Standing Wave

The sound waves of the pre-set frequency are sent into the resonator. As the resonator is closed on the other side, the initial wave gets reflected back into the resonator. Because of this, interference between the original and the reflected wave occurs. This interference may be of two forms; either constructive interference or destructive interference. When both the waves are of the same phase, constructive interference will happen. On the contrary, the presence of opposite phase will result in destructive interference. When this process happens inside a closed medium, the waves created are called standing waves.

Thermoacoustic Effect

When the sound wave from the acoustic driver is passed through a resonator at a particular frequency, the pressure pulsations form a standing wave. This causes the oscillatory motion of the gas in the resonator along the axial direction. The combination of the pressure pulsations and oscillatory motion of the gas inside the tube causes heat transfer, when there exist a thermal contact of the gas with a stationary surface i.e., the stack.

Refrigeration using Thermoacoustic effect

Based on the expansion and compression of the gas by sound, the heating and cooling (temperature difference) occurs on both the ends of the stack on account of the thermoacoustic effect. The reduced temperature at the cold end of the stack is taken out with the help of using a heat exchanger. This reduced temperature can be used for the refrigeration purposes.

Review on Thermoacoustic Refrigeration

Refrigeration by conventional methods plays a key role in the modern world. The refrigeration process occurs by the process of vapour compression, which uses a specific refrigerant. The refrigeration system has undergone a lot of development after its introduction in the beginning of 19th century. However, the conventional system of refrigeration poses a major threat to the environment by the generation of ozone depleting green-house gases. Blends of carbon, hydrogen, fluorine and chlorine are mixed in various ratios to attain the required temperature. Potential to cause global warming is also high. Also, it involves high energy cost. After the impact of these adverse effects was determined, efforts are being made continually to move over from conventional refrigeration. Thermoacoustic refrigeration is a good alternative as it offers the desired level of cooling without using any harmful substances. Mathewlal. T, PranavMahamuni, MandhataYadav, Florian Zinc and many other authors have stressed on the need for alternate refrigeration system and the benefits of using Thermoacoustic refrigeration[3,4,10,27]. Use of harmless refrigerants like air, helium or any inert gas is environment friendly. Thermoacoustic refrigeration technique offers other added advantages of less maintenance cost as there are no moving parts, and hence, there is no requirement of lubrication system.

Thermoacoustics is the combination of thermodynamics and acoustics. It involves the study of transfer of heat by using sound waves. Sound waves, of high intensity are used for the purpose of cooling. Mathewlal. T et al., designed and fabricated a Thermoacoustic model and tested it[3]. The resonator used was of quarter wavelength type that used air in the ambient condition as the working fluid. While the model was tested, that the temperature at the hot end of the stack was increasing at a faster rate than the temperature at the colder side of the stack. The reduction in the temperature was retarded because the heat from the hot end of the stack was flowing back to the cold side and raising the temperature, instead of being dissipated to the surroundings. To solve the foresaid problem, heat exchangers that are made of copper wool and copper mesh that has the same porosity as that of the stack could be used. Providing such heat exchangers at both the ends of the stack might help to prevent heat accumulation.

A study of the Thermoacoustic system was conducted by PranavMahamuniet al[4]. Parameters such as frequency and mean pressure have a significant effect in creating the temperature difference across the ends of the stack. The model was tested was tested for various frequencies from 250 Hz to 500 Hz in steps of 50 Hz. The results obtained indicate that the temperature at the hot end increases with the frequency and then remains stable. The time taken to stabilize increases with the corresponding increase in the mean pressure. Performance of the Thermoacoustic system can also be increased by the variation in the cooling loads. Increasing the cooling loads causes more heat to be pumped to the hot end of the stack, which results in increasing the temperature difference. Also, the temperature difference is dependent on the pressure and, is maximum at a particular pressure.

NormahMohd-Ghazali et al designed a portable counter top Thermoacoustic Cooling apparatus, made of a PVC resonator of 60mm diameter[5]. The temperature which was initially at 24°C came down to 18.5°C within a minute. A drop in temperature was observed from 23°C to 8°C, when an acrylic resonator of 110mm diameter was used. From these tests, it can be observed that this system of refrigeration could be used for specific applications, if not for general purpose applications.

Owing to the benefits and ideal potential of Thermoacoustic refrigeration system to replace the conventional refrigeration system, efforts are being made to improve the COP of the system. While the focus is on improving the performance, importance is to be given to the resonator geometry, stack, the acoustic driver, the frequency of sound wave and heat exchangers. MandhataYadav has stated that the researchers still now has focused on the length of the stack and its position[10]. However, there is a lack on the ideal model of the stack. Research is to be made on stacks of different materials and in different gases, in order to find the best combination that will yield a better COP.

The length of the resonator also affects the performance of the refrigerator. N. M. Hariharan constructed a Thermoacoustic engine, which produces high energy sound waves from heat[12]. The sound waves are used to drive a thermoacoustic refrigerator or a cryo-cooler. This set up has been built on the basis of linear TA model and other design parameters. Results obtained indicate that as the length of the resonator increases, the difference in the temperature across the stack and the mean pressure amplitude increases and hence, the cooling by the system also increases.

The impact of the resonance tube on the performance of the Thermoacoustic stack was studied by Channarong Wantha[22]. The key component of a standing wave Thermoacoustic refrigerator is the resonance tube. The performance of the system increases with appropriate resonator length. Results obtained indicate that the optimal operating frequency and that obtained from the design based on the equations of half wavelength differs from each other. In order to compensate for some effects, the length of the resonator is increased. Under the optimal match between the operating frequency and the resonator length, an increase in the difference in temperature by approximately 55.67% was observed. Poor match will cause a decline in the stack performance.

N. M. Hariharan designed and fabricated a Twin Thermoacoustic Heat Engine [39]. The device generated high intensity sound waves. The performance of the system is analysed by varying the length of the resonator and the working fluid. The performance of the system is measured in terms of the difference in temperature, pressure amplitude of the oscillations and the resonance frequency. Simulations of the system using DeltaEC was done and the deviations obtained from the experimental results were within 10%. These deviations are observed due to variations in the uniformity of stack spacing and the cross section. The results obtained indicate that as the half-wave resonator length increases, the temperature difference decreases. This effect is lowest in helium followed by nitrogen and then argon. As the resonator length increases, resonant frequency decreases and the pressure oscillations increases.

Konstantin Tourkov has explained on the effect of the resonator curvature on the Thermoacoustic effect [38]. CFD studies aim at quantifying the effect of resonator curvature. However, these seem to be insufficient as several mechanisms that are difficult to model using CFD occur in a thermoacoustic engine. Hence, future work in the area is required. A standing wave engine design with a square channel ceramic stack is used. The temperature at the ends of the stack and the pressure at the anti-nodes are examined, under the influence of the resonator curvature. Increase in the curvature adversely affects the pressure level of the sound and causes increase in the difference in temperature across the ends of the stack at a constant heat input. A close relationship is presented between the temperature variation across the stack ends and the level of the sound pressure.

A study on the influence of the buffer on the resonance frequency of a Thermoacoustic engine was studied by G. B. Chen[43]. Frequency matching is one of the great important aspects to a thermoacoustic drive pulse tube refrigeration system. Fluid impedence method is introduced in order to compute the resonance frequency of TA engines. Calculations are made with different arrangements of buffer for TA engines are carried out. The influence of buffer arrangements and the volume on the resonance frequency and the acoustic power of the engine have also been discussed. The method of fluid impedance can be applied for simple arrangements and as well as complex hybrid arrangements. Based on the results obtained, it can be brought to a conclusion that an acoustic structure like buffer has a significant influence on the resonance frequency and other such performance of the TA engines.

The effect of different working gases on the performance of a small Thermoacoustic Stirling Engine was investigated both experimentally and numerically by M. Chen[42]. The investigation gave focus to the operating frequency, onset temperature, pressure amplitude and the temperature characteristics after onset. Sound with frequencies of 45 Hz, 42 Hz and 130 Hz were respectively passed through working gases nitrogen, argon and helium. It was observed that the engine operated with helium, worked under wide range of pressure than argon and nitrogen. For each of the working media, there was an optimal mean pressure for the minimum onset temperature. Using nitrogen and argon as the working gas rather than helium, another optimal mean pressure for the highest pressure ratio was obtained. The loop dimension was indispensible in the determination of the frequency and the highest power ratio was observed in the resonator cavity. Further investigation and effort are required to improve the overall performance of small TA engines and to utilize the low quality heat or energy source like solar power to drive the refrigerators in a limited space.

Thermoacoustic refrigerator works with high amplitude sound waves created from an acoustic driver. The acoustic source is coupled to the resonator. This acoustic coupling between the loud speaker and the resonator in a standing wave Thermoacoustic drive was explained by David Marx[24]. Linear acoustic equations and linear model of the loud speaker can be used to analytically calculate this coupling. For low values of excitation voltage corresponding to the low acoustic pressure, the comparisons with the measurements are good. However, the measured drive ratios are found to be lower than predicted when there is an increase in the voltage. This observed disagreement grows as the square of the pressure amplitude. This clearly indicates the presence of a non-linear phenomenon. The non-linearities may be associated with harmonic generation; turbulence and the loudspeaker behaviour are low. The possible cause for the deviation and the observed difference may be the minor losses.

The stack is one of the most important parts of a thermoacoustic system that affects its performance. A. C. Alcock investigated the performance of the ceramic substrates used as a stack material in standing wave Thermoacoustic refrigeration[2]. The geometric configuration of the stack influences the performance of the system which was studied. The porosity of the stack, its length and the position of the stack in the resonator were varied. Cordierite honeycomb ceramic stack of four different lengths (26 mm, 48 mm, 70 mm, 100 mm) with square cross sections were used for the test. Guidance on the design of the stack and the best possible configuration are also provided. Another important consideration is the material choice of the stack and the method of manufacturing. Results obtained indicate that the resonant frequencies were different for each position of the stack. It was observed that the difference in temperature becomes maximum, when the stack is positioned closer to the pressure antinode. The length of the stack had very insignificant effect on the performance of the device. The relation between the temperature difference and the geometrical parameters were non-linear. The author states that further study on the interdependency between the frequencies and the geometrical parameters is required.

Thermoacoustic refrigeration utilizes the interactions of the high intensity sound waves and the medium to produce the refrigeration. Compression and rarefaction of the gas occurs when the sound travels longitudinally in the medium causing subsequent heating and cooling. Stack is the medium of heat transfer and is the heart of the system. An overview of the design of the stack is presented by Bhansali. P. S [7]. Thermal properties such as thermal conductivity and the specific heat are important for the design of stack. Optimal spacing of the stack plates based on the thermal penetration depth and the viscous penetration depth are discussed. Stack made of vitreous carbon in various geometries like parallel plate, porous type, spiral type and parallel plate type. The important characteristics of the stack are high heat capacity and low thermal conductivity. Stack geometry and spacing play a major role in the refrigeration. Very less spacing gives rise to high viscous losses whereas more spacing leads to less volume of gas to involve in thermal interaction. Optimal stack spacing of three times the thermal penetration depth is suggested. The simplest design is spiral type stack. Pin stack offers improved ratio of energy transmitted to viscous losses.

S. Balonji conducted an experiment to evaluate the performance of different stack made of ceramic materials with square pores [8]. A standing wave thermoacoustic refrigerator of 465mm length was designed by using a numerical approximation with the use of a modelling code called as Design Environment for Low Amplitude Thermo Acoustic Energy Conversion (DeltaEC). The configuration of the stack such as diameter, length, porosity and position of the stack has significant effect on the performance of the system. The main objective of the work is to identify and select the best geometric configuration of the stack. By simulating using DeltaEC, the performance in terms of COP was evaluated by varying geometric configurations of stack and the best condition was selected.

A small scale thermoacoustic refrigeration system was fabricated and studied experimentally by B. Ananda Rao[13]. Through his experiment, he found that the variation in the temperature difference across the stack was under 0.5^{o}C when there was no stack placed inside the resonator. When the stack was used, the difference in temperature of 15^{o}C was obtained after 300 seconds. The maximum difference in temperature was found to occur when the stack is placed at the pressure antinodes. The insulation around the resonator was found to have very less effect on the obtained refrigeration.

Ikhsan Setiawan conducted an experimental study on the thermoacoustic cooling system using two stacks in a straight resonator tube [11]. The resonator was made of PVC of length 112cm using air at atmospheric pressure at the frequency of 152 Hz. Stacks are made of parallel plate type with thickness of 0.3 mm and spacing of 0.85 mm. This spacing is about four times the thermal penetration depth. The length of the stack is 10cm and the diameter is 20 cm. The frequency range is 130 – 160 Hz and the input electric power is 40 W to 160 W. The stacks are positioned at 8 cm and 25 cm in the resonator. It was observed that the maximum temperature difference occurs when the stacks are placed at the ends of the tube near the pressure antinodes at a frequency of 147 Hz. Higher temperature occurs at higher input power. There was no much difference in temperature after 15 minutes of operation. The operating frequency is slightly below the resonant frequency. This shift in frequency is due to the use of stack and the diaphragm. Heat conduction across the stack is affected by the temperature decrease at the cold end of the stack. The stack that was placed near the closed end of the stack produced better temperature difference than that placed near the diaphragm.

N. M Hariharan also agrees that the stack parameters such as the thickness of the plate and the spacing, along with the resonator length affect the performance of the system[12]. His study shows that as the thickness of the plate is increased, the difference in temperature also increases. More pressure amplitude was found to occur for less thickness of the stack plate. Also, increase in the plate spacing and the resonator length causes a reduction in the working frequency. Reduction in the operating frequency leads to reduction in the temperature difference.

A study on the performance of a thermoacoustic refrigerator was done using stacks of two different spacing of 0.4 mm and 0.8 mm and the temperature difference was observed by N. M. Hariharan[17]. Stacks made of low thermal conductivity materials like mylar sheets and photo film were used. Helium was used as working medium at 1 MPa at a frequency of 460 Hz. Pressure Amplitude of 0.07 MPa was obtained from twin thermoacoustic prime mover. Results obtained indicate that a temperature difference of 16^{o}C was obtained in Mylar sheet stack of 0.4 mm spacing. The temperature difference obtained was higher for Mylar sheet with lesser spacing. In the case of photographic film, the temperature rise at the hot end was higher. Also, twin thermoacoustic prime mover acts as an efficient drive for the system.

The effect of the positioning of the stack, also known as regenerator, on the intensity of the thermoacoustic effect in a looped-tube travelling wave thermoacoustic engine was described by Konstantin Tourkov[30]. Travelling wave thermoacoustic engine works based on the principle of an acoustic wave travelling through the loop of an engine across the regenerator, with the pressure and velocity curves in phase and thus, amplifying the acoustic effect. Increasing the intensity of effect while the input energy is kept constant increases the efficiency of thermoacoustic engine and the COP of thermoacoustic refrigerator. Proper positioning of the stack increases the intensity of the standing wave device. Amount of cooling created from the given heat input can take place from more effective conversion of thermal energy to thermoacoustic energy and hence, the COP of the system increases.

The heat transfer at the heat exchanger of the thermoacoustic system was experimentally studied by Emmanuel C. Nsofor[32]. The study focused on the oscillatory flow of heat transfer at the heat exchanger. The factors that affected the heat transfer were identified. The results obtained were correlated in terms of Prandtl number, Nusselt number, and Reynolds number in order to obtain new correlation that are useful for the heat transfer that occurs at the heat exchangers. Usage of straight flow heat transfer correlation for the analysis and the design of the system results in errors that are significant. The relationship between oscillatory heat transfer coefficient at heat exchanger, the frequency of oscillation and the mean pressure were described. The heat transfer coefficient increases with higher mean pressure, if the system is operated at the corresponding resonant frequency. The error caused by the usage of straight flow analysis is because of the nature of the oscillator flow does not allow the fluid particles close to the solid surface in order to make as much contact with the heat exchanger surface as the particles in the straight flows.

The effectiveness of the thermoacoustic refrigeration system was examined by Kaushik S. Panara[6] and B. Ananda Rao[13]. Kaushik S. Panara brings out that the performance of the refrigerator depends on the working gas, the shape of the resonator, pressure inside the resonator tube, stack material, length and its position. Thermoacoustic refrigeration system offers the combined benefits of providing heating and cooling simultaneously. Results obtained indicate that a variation in the temperature of only 0.5^{o}C was observed inside the resonator tube without the stack. The same was confirmed by the experiments of AnandaRao. Presence of stack creates a difference in temperature. The measured difference is 7^{o}C within 18 minutes of operation by Kaushik S. Panara and 15^{o}C under 300 seconds in the case of the experiment done by AnandaRao. The position of the stack is of essential importance in order to get maximum temperature difference and it occurs at the pressure antinodes. The input power as well as the effectiveness of the acoustic driver plays a major role in creating the maximum temperature gradient. The insulation around the resonator has very little effect on the temperature difference. The optimal frequency that is essential for the maximization of the efficiency was obtained by trial and error method, because the equation to calculate the frequency was found to be ineffective. The heat may escape from the refrigerator if the parts are not properly sealed.

The methods to improve the performance and the temperature difference were detailed by Jithin George[15]. Increasing the length of the resonator causes an increase in the temperature at the hot end of the stack. Use of aluminium plug improves the performance when compared with plastic plug by creating more difference in temperature. The increased temperature difference can be achieved by the use of heat exchangers at the ends of the stack. A stack made of low conductivity material would enable to reduce the heat diffusion across the stack. Optimum spacing of the plates in the stack is also essential for the improved performance.

Ramesh Nayak. B conducted an experiment to evaluate the performance of thermoacoustic refrigeration system under various operating conditions and stack geometries [16]. The system consisted of a resonator made of aluminium, the inner face of which was coated with Polyurethane material with an objective of reducing the heat loss. The difference in temperature across the stack can be increased by increasing the acoustic power. His results indicated that higher temperature difference was obtained using parallel plate stack. The temperature difference increases as the heating load increases. Small Thermoacoustic refrigeration system was constructed with inexpensive and readily available parts by SreeneshValiyandi[18]. He suggested that in order to obtain higher cooling effect higher heat carrying capacity materials could be used and inert gases could be used as working fluid. Using heat sink might allow excess of heat to dissipate.

A. Widyaparaga has described that the direction of heat pumping can be altered by altering the acoustic field [35]. So the device can function as a heater or a cooler without the addition of complicated machinery. A thermoacoustic heat pump was constructed with dual opposing acoustic drivers connected to a resonator. A regenerator constructed by means of steel mesh layers was placed in the centre of the resonator tube in order to investigate the effect of alteration of the acoustic field due to the interaction of opposing traveling wave. Altering the phase difference and the magnitude between the waves generated by the acoustic drivers, the acoustic field was manipulated. The results indicate that the acoustic flow of power on both the sides of the stack altered the direction of the pumped heat. The travelling wave component and the standing wave component also affect the heat pumping direction.

The influence of wave patterns and the frequency on the thermoacoustic cooling effect was investigated by Yousif A. Abakr[9]. Simple thermoacoustic refrigerator system was designed and tested for the effects of wave patterns and frequency on the cooling. It was observed that the square wave pattern yielded better results when compared with other wave patterns. The maximum temperature difference of 28^{o}C was observed with square waves; sine waves produced temperature difference of 26°C and the triangle waves produced 21°C difference in temperature.

A three dimensional investigation of thermoacoustic fields in a square stack was done by Ahmed I. Abd El-Rahman[21]. The thermo-viscous behaviour of the oscillating gas in a porous medium enables the conversion of sound into heat in the typical standing wave refrigeration process. A new three dimensional finite volume model was presented that solves the full non-linear thermo-hydrodynamic laminar flow equations in three dimensions and examines heat transfer between the thermoacoustically oscillating gas and the surrounding surface in a thermoacoustic stack made of square pores. The temperature variation with time across the stack ends was investigated by the model and also, the axial flow velocity profiles at the stack centre and the mean energy flux density near the stack ends are analysed. Flow streaming and the mean vorticity field are also calculated. More heat transfer across the stack is expected with square pore geometry than the corresponding parallel plate geometry. Future work may focus on extending the study to include high drive ratios, in which the potential of flow transitions from laminar to turbulent is no longer trivial.

Thermoacoustic system has the potential of developing renewable energy systems by the utilization of waste heat or solar energy. An algorithm based on simplified linear TA model was developed by HadiBabaei that has the ability to design thermoacoustically driven refrigerators [23]. This is a new feature based on the energy balance to design a thermoacoustic engine and acoustically driven refrigerators. It has been found that the results of the algorithm are in agreement with the results obtained from the computer code DeltaEC.

Numerical Simulation for turbulent flow heat transfer of thermoacoustic cooler was done by Jiangrong Xu[25]. A theory model of numerical simulation was provided and the thermoacoustic cooling model was simulated. The focus is given to the temporal and the spatial variation of the parameters like velocity, temperature turbulent intensity and density. The resonator and the heat exchangers were treated as porous area with 15 atm pressure, 20Hz frequency and the lowest temperature of 243K was achieved.

HasserYassen made an attempt to find the impact of temperature gradient on the thermoacoustic refrigeration system [26]. Low technological strategies are essential particularly in the fabrication of stack. The new design strategies were modified in order to obtain new software for sizing a thermoacoustic device to be manually built and also determine the impact of the temperature gradient across the stack. The various parameters like the heating capacity, cooling capacity, stack spacing and the mean pressure were chosen in order to fit the needs. Optimum temperature gradients were also included.

The CFD analysis of thermoacoustic cooling was done by Florian Zink [28]. In thermoacoustic energy conversion, the application of numerical analysis techniques, particularly, Computational Fluid Dynamics (CFD) Analysis has gained importance. The efforts made previously focused on single thermoacoustic couples that were subjected to thermoacoustic effect using an oscillatory boundary condition. It is computationally expensive to conduct CFD analysis of the entire thermoacoustic system. The prescribed work examines the simulation of an entire thermoacoustic engine that includes thermoacoustic refrigeration. The cooling of the working gas in the stack is demonstrated by the interaction of thermally generated sound waves. Temperature reduction below the ambient temperature was simulated by the new model and it was found to be consistent with the similar physical model. Location of the stack near the pressure node is of prime importance as it should yield better results.

Florian Zink also illustrated the geometric optimization of the thermoacoustic system, count the thermal losses to the surroundings that are mostly disregarded[33]. A simple TA engine is used to demonstrate the methodology. Finite element method was used to model the driving component and the stack. The dimensions are varied in an attempt to find the optimal design where the thermal losses are less. The phenomenon of thermoacoustic involves consideration of acoustic power, capacitive and viscous losses of the regenerator. The optimization takes into consideration four weighted objectives and it is conducted with Nelder-Mead Simplex method. When the thermal losses are to be minimized, the regenerator must be designed as small as possible. It has been found that there is an optimal regenerator diameter for a particular length. The results are given for a variety of materials along with the weights of each objective. In a standing wave engine, heat transfer from the gas to solid has to be delayed in order to get correct phasing between pressure and velocity oscillations. This delay is shorter as small as the channel is. For ideal contact, equal to or lesser than the thermal penetration depth, there is no delay. There is a need for improved models of thermoacoustic work and loss mechanisms.

The parameter estimation for the characterization of thermoacoustic stacks and regenerators was done by MatthieuGuedra[40]. The study deals with the in-situ characterization of open cell porous stack. An inverse method is used to estimate the geometric and the thermal properties of the stack surrounded by the heat exchangers and connected to the thermal buffer tube to form the thermoacoustic core. The experimental data obtained from different stacks under varying heating conditions are used to fit the theoretical forward model by adjusting the geometric parameters of sample and heat exchanger coefficients. It was found that carbon foam allows getting higher temperature gradients.

M. E. H. Tijani described the design of a thermoacoustic refrigeration system by using the linear thermoacoustic theory[14]. There are large numbers of parameters to be considered while designing. Hence, some parameters with dimensionless independent variables are introduced. Guidelines for the design, development and optimization of different parts of the system are discussed. The large number of parameters can be reduced by using dimensionless parameters and, making the choices on some parameters.

Of thermoacoustic refrigeration systems have been developed with modified design of the simple thermoacoustic refrigeration system. EsmatullahMaiwanSharify constructed a double loop type travelling wave thermoacoustic refrigerator system that is driven by a multi stage travelling wave thermoacoustic engine[19]. The design consisted of three etched stainless steel type mesh regenerators installed inside the prime mover loop. One regenerator was fixed in the refrigerator loop. His experiments concluded that as there is an increase in the temperature at the hot end of the regenerator, the COP of the system increases. The cooling performance of the system can be extended up to a considerable extent by the installation of multiple regenerators in the vicinity of the sweet spot of the prime mover.

The acoustic field characteristics and performance analysis of a looped travelling wave thermoacoustic refrigerator was done by T. Jin [20]. A looped travelling wave thermoacoustic refrigerator with one engine stage and one refrigerator stage is proposed. Emphasis is given to the high normalized acoustic impedance, the volumetric efficiency required and the proper phase relation between the pressure and velocity, close to the travelling wave in the regenerators of both the refrigerator and engine. Analysis on the utilization of low grade thermal energy and the impact of the heating and cooling temperatures that are critical to refrigeration applications are conducted. The increase in the heating or cooling temperature can realize the near travelling wave acoustic field in the regenerated. The normalized acoustic impedance in the engine's regenerator can be raised and that in the refrigerator's regenerated be reduced by elevating the heating temperature and by lowering the cooling temperature.

MaximePerier-Muzet designed and analysed the dynamic behaviour of a cold storage system combined with a thermoacoustic system that is solar powered[29]. A thermoacoustic engine produces acoustic work by the utilization of the waste heat in a heat powered thermoacoustic refrigerator. This is coupled to a thermoacoustic cooler that enables the conversion of acoustic energy into cooling effect. The study has demonstrated the usage of solar energy as the source of thermal energy for a low power heat driven thermoacoustic refrigerator. The objective is to study the KW scale solar thermoacoustic refrigeration capable of reaching the temperatures required for industrial refrigeration domain. In order to take care of the fluctuations and guarantee the cooling required, the refrigerator system is combined with a latent heat storage system. The system is capable of supplying a cooling power of 400 Watts at a temperature equal to or lesser than -20^{o}C with best storage design. The average COP of the solar thermoacoustic refrigeration system is equal to 21%.

M. Nouh constructed a piezo driven thermoacoustic refrigerator with dynamic magnifiers[31]. Large number of thermoacoustic regenerators has been used till now using electromagnetic loudspeakers for the generation of acoustic input. The design, construction and the operation of a piezo driven thermoacoustic refrigerator is explained in detail. The acoustic driver can be coupled to an elastic structure called a dynamic magnifier in order to increase the performance of the system. The proper selection of the magnifier parameters can increase the performance of the system by increasing the magnitude of pressure oscillations across the stack and thus, increasing the temperature difference. The magnified refrigerator demonstrated the effectiveness of piezoelectric actuation in moving 0.3 W of heat with an input power of 7W across a 10^{o}C difference in temperature. The theoretical predictions from the discussed model based on the mathematical model were validated against the experimental prototype of the device. Thus, piezo-driven thermoacoustic refrigeration using dynamic magnifiers proves to be an efficient means of increasing the cooling outcome of the system.

Jing Yuan Xu constructed a looped three stage thermoacoustically driven cyrocooler which proves to be an efficient system for liquefaction of natural gas[36]. A number of thermoacoustic heat engines of different diameters are connected end-end by means of small diameter resonance tubes. A pulse tube cyrocooler is connected to the branch of the last stage engine. The system realized cascaded acoustic power amplification with only a single power output. The device was also numerically investigated. Comparison was made with the existing pulse tube cyrocooler. The obtained results indicate the superior performance of the system. The distribution of some key parameters and the energy losses involved are also detailed.

Shinya Hasegawa designed a thermoacoustic refrigerator that was driven by a low temperature-differential and high efficiency multistage thermoacoustic engine[41]. A multistage thermoacoustic engine has the potential to lower the critical onset temperature, which can be successfully lowered further by means of multistage amplification. One of the reasons for the low efficiency is because of the reason that it is not possible to set all the regenerators of the multistage thermoacoustic engine at the peak of the real part of the acoustic impedance distribution. Hence, it is essential to develop a thermoacoustic engine that has both high efficiency and low temperature oscillation. Numerical calculations were done on the double loop thermoacoustic refrigerators driven by multistage thermoacoustic engine. The configuration that enabled low temperature oscillation and high efficiency was determined. The oscillation obtained at a temperature difference of 110.8 K, equivalent to industrial waste heat temperature with an efficiency of 21% is achieved.

Thermoacoustic refrigeration systems offer many advantages over the conventional refrigeration systems. Thermoacoustic system has the potential to develop renewable energy systems by the utilization of waste heat or solar energy as stated by HadiBabaei[23]. A. C. Alcock and Mathewlal. T have made it clear that the environmentally friendly attributes of the system and the benefit of no moving parts and lubrication have turned the attention of researches towards this field [2,3].Global warming potential and ozone depleting potential are less [26].

Although the current applications of thermoacoustic refrigeration system are limited, with further studies and investigations, this method of refrigeration can be used in many domains. Some of the areas where the system can be potentially applied are in the liquefaction of natural gas[1], in obtaining heating and cooling simultaneously[35], utilization of waste heat in industries[37]. J. A. Mumith designed a thermoacoustic heat engine for the low temperature waste heat recovery in food manufacturing [37], for cooling applications in space (STAR-Space Thermo Acoustic Refrigerator), cooling of electronic components in ships and in cooling of ice creams.

Efficient thermoacoustic refrigeration systems are being used in the industries. If the problem in its size can be solved then the market of applying this technique can be made broader. The Total Equivalent Warming Impact (TEWI) of thermoacoustic refrigerator is compared with that of the conventional cooling in vehicles by Florian Zink[27].These types of refrigerators can be powered by waste heat. The target areas of applications are also suggested. These systems can be applied in transportation of perishable goods, in the transportation of medical supply in trains and trucks. However, depending on the requirement the amount of cooling required may vary. For example, ice creams require -23^{o}C of cooling, vegetables require -18^{o}C, meat requires -1^{o}C and fresh vegetables require 1^{o}C of cooling. Modification of the size and the shape of the thermoacoustic refrigerator are required for applying it in engines where a straight resonator is not possible. The system upon development by improving its components can become a supplement to conventional refrigeration systems.

The waste heat from the industries is available for reuse. In the work done by J. A. Mumith, investigations are done on the utilization of thermoacoustic heat engine in order to utilize the waste heat from the baking ovens during biscuit manufacturing[37]. The design parameter values of the device are determined by applying an iterative design methodology with a view of maximizing the output and efficiency by the maximum utilization of waste heat. DeltaEc is the core of the methodology employed. The results of the experiment indicate that the low temperature industrial processes are also applicable for the recovery of waste heat. As a single thermoacoustic heat engine produces less level of thermal power, using thermoacoustic heat engine together can produce higher level. For effective waste heat utilization, heat exchanger design is crucial.

Though thermoacoustic refrigeration system has wide potential and offers more benefits when compared with the conventional vapour compression refrigeration system, one major factor that affects the implementation of this technique in various applications is the lesser efficiency and the COP of the system. Future works in the domain may be directed towards improving the efficiency and the COP of the system by varying the resonator geometry, by changing the parameters of the acoustic driver, by using stacks of different materials and geometry and by varying the working medium. There is a lack of the ideal model of the stack and the working fluid. The relationship among the various components and the factors in influencing each other and determining how they affect the cooling effect are to be clearly identified. The area of application of thermoacoustic refrigeration system is to be widened by modifying the system according to the needs of application.

Conclusion

The various important studies that have been made on the thermoacoustic refrigeration system have been presented. Thermoacoustic refrigeration can greatly reduce the emission of harmful gases like ChloroFluoro Carbon (CFC) because of the use of eco-friendly refrigerants like helium instead of harmful chemical fluids and hence can become an alternative to conventional refrigeration. With the potential of reducing global warming and ozone depletion, thermoacoustic refrigeration system is one of the harmless types of refrigeration system. This review can serve as the basis for the design of the system by taking into effect the influence of various parameters on the system. The methods to improve the performance of the system and the means to optimize the device have been pictured clearly.The software simulation techniques and the numerical models are described and the potential areas of application of the system have been detailed. This field offers a wide range of scope for further research for improving the efficiency and the Coefficient of Performance. This field is gathering the attention of many researchers as it combines both the disciplines of thermal and acoustics and could replace the conventional refrigeration in future.

References

1. Limin Zhang, Yanyan Chen, ErcangLuo, ANovel Thermoacoustic System for Natural Gas Liquefaction, The 6th International Conference on Applied Energy (ICAE), Energy Procedia, 2014, 1042-1046.
2. A. C. Alcock, L. K. Tartibu, T. C. Jen, Experimental Investigation of Ceramic Substrates in Standing Wave Thermoacoustic Refrigerator, International Conference on Sustainable Materials Processing and Manufacturing (SMPM), Procedia Manufacturing,2017, 79-85.
3. Mathewlal. T, GauravSingh, ChetanDevadiga, NehalMendhe, Demonstration of Thermo Acoustic Refrigeration by Setting up an Experimental Model, IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 2014, 29-33.
4. PranavMahamuni, Pratik Bhansali, Nishak Shah, Yash Parikh, A Study of Thermoacoustic Refrigeration System, International Journal of Innovative Research in Advanced Engineering (IJIRAE), 2015, 160-164.
5. NormahMohdGhazali, Mahmood Anwar, Nurudin H. M. A. Settar, Thermoacoustic Cooling with No Refrigerant, International Journal of Technology,2011, 234-241.
6. Kaushik S. Panara, AmratM.Patel. Jigar D. Patel, Thermoacoustic Refrigeration System Setup, International Journal of Mechanical Engineering and Technology (IJMET), 2015, 6, 01-15.
7. Bhansali P. S, Patunkar P. P, Gorade S. V, Adhav S. S, Botre S. S, An Overview of Stack Design for Thermoacoustic Refrigerator, International Journal of Research in Engineering and Technology (IJRET), 2015, 4, 68-72.
8. S. Balonji, L. K. Tartibu, T. C. Jen, Performance Evaluation of Ceramic Substrates for Cooling Applications in Thermo-Acoustic Refrigerators, International Conference on Sustainable Materials Processing and Manufacturing (SMPM), Procedia Manufacturing, 2017, 131-137.
9. Yousif A. Abakr, Mushtak Al-Atabi, Chen Baiman, The Influence of Wave Patterns and Frequency on Thermo-Acoustic Cooling Effect, Journal of Engineering Science and Technology,2011, 6, 392-396.
10. Mr. MandhataYadav, Kuldeep I. Solanki, Effect of Working Gases and Stack Material on a Thermoacoustic Refrigerator – A Review, International Journal for Innovative Research in Science & Technology (IJIRST),2015, 1, 142-144.
11. IkhsanSetiawan, AgungBambangSetio-Utomo, Makoto Nohtomi, Masafumi Katsuta, Experimental Study on Thermoacoustic Cooling System with Two Stacks in a Straight Resonator Tube, 10eme CongresFrancaisd'Acoustique, 2010.

12. N. M. Hariharan, P. Sivashanmugam, S. Kasthurirengan, Influence of Stack Geometry and Resonator Length on the Performance of Thermoacoustic Engine, Applied Acoustics, 2012,1052-1058.
13. B. AnandaRao, M. Prasanth Kumar, D. SrinivasaRao, Design and Experimental Study of Small-Scale Fabricated Thermo-Acoustic Refrigerator, International Journal of Engineering Trends and Technology (IJETT),2013, 4, 3830-3836.
14. M. E. H. Tijani, J. C. H. Zeegers, A. T. A. M. de Waele, Design of Thermoacoustic Refrigerators, Cryogenics, 2002, 49-57.
15. Jithin George, Loud Speaker Driven Thermo Acoustic Refrigeration, International Journal of Scientific &Engineering Research,2016,7, 465-468.
16. Ramesh Nayak. B, Bheemsha, Pundarika. G, Performance Evaluation of Thermoacoustic Refrigerator Using Air as Working Medium, SSRG International Journal of Thermal Engineering (SSRG-IJTE), 2015, 1, 01-07.
17. N. M. Hariharan, P. Sivashanmugam, S. Kasthurirengan, Experimental Investigation of a Thermoacoustic Refrigerator driven by a Standing Wave Twin Thermoacoustic Prime Mover, International Journal of Refrigeration, 2013, 2420-2425.
18. SreeneshValiyandi, Design and Fabrication of Thermoacoustic Refrigeration System, 4th International Conference on Science, Technology and Management (ICSTM-16), 2016, 236-245.
19. EsmatullahMaiwandSharify, Shinya Hasegawa, Travelling Wave Thermoacoustic Refrigerator Driven by Multistage Traveling-Wave Thermoacoustic Engine, Applied Thermal Engineering, Accepted manuscript-2016.
20. T. Jin, R. Yang, Y. Wang, Y. Feng, K. Tang, Acoustic Field Characteristics and Performance Analysis of a Looped Travelling-Wave Thermoacoustic Refrigerator, Energy Conversion and Management, 2016, 243-251.
21. Ahmed I. Abd El-Rahman, Waleed A. Abdelfattah, Mahmoud A. Fouad, A 3D Investigation of Thermoacoustic Fields in a Square Stack, International Journal of Heat and Mass Transfer, 2017, 292-300.
22. ChannarongWantha, KriengkraiAssawamartbunlue, The Impact of the Resonance Tube on Performance of a Thermoacoustic Stack, Frontiers in Heat and Mass Transfer (FHMT), 2011, 01-08.
23. HadiBabaei, Kamran Siddiqui, Design and Optimization of Thermoacoustic Devices, Energy Conversion and Management, 2008, 3585-3598.
24. Davis Marx, Xiaoan Mao, Artur J. Jaworski, Acoustic Coupling Between the Loudspeaker and the Resonator in a Standing-Wave Thermoacoustic Device, Applied Acoustics, 2006, 402-419.
25. JiangrongXu, Dianpeng Zhao, Fang Chen, ShanshanXu, Numerical Simulating for Turbulent Heat Transfer of Thermoacoustic Cooler, International Workshop on Automobile, Power and Energy Engineering, Procedia Engineering, 2011, 789-795.
26. Nasser Yassen, Impact of Temperature Gradient on Thermoacoustics Refrigerator, International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability (TMREES15), Energy Procedia, 2015, 1182-1191.
27. Florian Zink, Jeffrey S. Vipperman, Laura A. Schaefer, Environmental Motivation to Switch to Thermoacoustic Refrigeration, Applied Thermal Engineering, 2010, 119-126.
28. Florian Zink, Jeffrey S. Vipperman, Laura A. Schaefer, CFD Simulation of Thermoacoustic Cooling, International Journal of Heat and Mass transfer, 2010, 3940-3946.
29. MaximePerier-Muzet, Jean-Pierre Bedecarrats, Pascal Stouffs, Jean Castaing-Lasnignottes, Design and Dynamic Behaviour of a Cold Storage System Combined with a Solar Powered Thermoacoustic Refrigerator, Applied Thermal Engineering, Accepted Manuscript-2014.
30. Konstantin Tourkov, Laura Schaefer, Effect of Regenerator Positioning on Thermoacoustic Effect in a Looped Tube Traveling Wave Thermoacoustic Engine, Energy Conversion and Management, 2015, 94-100.
31. M. Nouh, O. Aldraihem, A. Baz, Piezo-Driven Thermoacoustic Refrigerators with Dynamic Magnifiers, Applied Acoustics, 2014, 86-99.
32. Emmanuel C. Nsofor, SerdarCelik, Xudong Wang, Experimental Study on the Heat Transfer at the Heat Exchanger of the thermoacoustic Refrigerating System, Applied Thermal Engineering, 2007, 2435-2442.
33. Florian Zink, Hamish Waterer, Rosalind Archer, Laura Schaefer, Geometric Optimization of a Thermoacoustic Regenerator, International Journal of Thermal Sciences, 2009, 2309-2322.

34. Mathew Skaria, K.K Abdul Rasheed, K. A. Shafi, S. Kasthurirengan, UpendraBehera, Simulation Studies on the Performance of Thermoacoustic Prime Movers and Refrigerator, Computers and Fluids, Accepted Manuscript-2015.
35. A. Widyaparaga, T. Hiromastu, T. Koshimizu, Deendarlianto, M. Kohno, Y. Takata, Thermoacoustic Heat Pumping Direction Alteration by Variation of Magnitude and Phase Difference of Opposing Sound Waves, Applied Thermal Engineering, Accepted Manuscript-2016.
36. JingyuanXu, Jianying Hu, Limin Zhang, ErcangLuo, A Looped Three-Stage Cascade Traveling-Wave Thermoacoustically Driven Cyrocooler, Energy, 2016, 804-809.
37. J. A. Mumith, C. Makatsoris, T. G, Karayiannis, Design of Thermoacoustic Heat Engine for Low Temperature Waste Heat Recovery in Food Manufacturing – A Thermoacoustic Device for Heat Recovery, Applied Thermal Engineering, (2014), 588-596.
38. Konstantin Tourkov, Florian Zink, Laura Schaefer, Thermoacoustic Sound Generation Under the Influence of Resonator Curvature, International Journal of Thermal Sciences, 2015, 158-163.
39. N. M. Hariharan, P. Sivashanmugam, S. Kasthurirengan, Efect of Resonator Length and Working Fluid on the Performance of Twin Thermoacoustic Heat Engine – Experimental and Simulation Studies, Computers & Fluids, 2013, 51-55.
40. MatthieuGuedra, Flavio C. Bannwart, Guillaume Penelet, PierrickLotton, Parameter Estimation for the Characterization of Thermoacoustic Stacks and Regenerators, Applied Thermal Engineering, Accepted Manuscript-2015.
41. Shinya Hasegawa, Tsuyoshi Yamaguchi, YasuoOshinoya, A Thermoacoustic Refrigerator Driven by a Low Temperature-Differential, High Efficiency Multistage Thermoacoustic Engine, Applied Thermal Engineering, 2013, 394-399.
42. M. Chen, Y. L. Ju, Effect of Different Working Gases on the Performance of a Small Thermoacoustic Stirling Engine, International Journal of Refrigeration, Accepted Manuscript-2014.
43. G. B. Chen, J. P. Jiang, J. L. Shi, T. Jin, K. Tang, Y. L. Jiang, N. Jiang, Y. H. Huang, Influence of Buffer on Resonance Frequency of Thermoacoustic Engine, Cryogenics, 2002, 223-227.

*****