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Review on Thermoacoustic Refrigeration

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Abstract *- The impact of hazardous refrigerants used in the conventional vapor compression refrigeration system and environmental issues related to VCRS system, alternative refrigeration technologies receive the attention of researcher's. The thermo acoustic refrigeration not utilizes any harmful refrigerants it uses only inert gasses as their working fluid, which does not cause any adverse effect on the environment. This review focuses on the various component of TAR and optimization methods use to improve the system performance. Most of the studies related to stack geometry, stack center position, resonance cavity and its length. The other work related with a heat exchanger, different algorithm's for system parameters optimization to get desired output along with COP of the thermoacoustic refrigeration system. Regarding current scenario, thermoacoustic refrigeration could be an emerging technology in a refrigeration system*

Keywords *- Environmental friendly refrigeration, cooling effect, performance optimization, resonance frequency.*

INTRODUCTION

Critical issues over the vapor compression refrigeration system (VCRS) demanding the elimination of harmful CFC and HFC refrigerants according to regulation led by Montreal protocols, studies related with thermoacoustic started in 1777 Byron Higgins observed thermoacoustic phenomenon with hydrogen flame into the close cavity, when gas flame puts into glass tube oscillation has occurred. The initiative has taken to introduce thermoacoustic phenomenon for cooling purpose in 1975, Hofler [38] built a first thermoacoustic cooler at Los Alamos National laboratory. The system consists of the loudspeaker at the front end of the tube with porous structure (stack) necessary to create temperature gradient with these heat is convey from left end of the stack to right end and finally to the surrounding. After this several attempts [1][2]are being made to construct the thermoacoustic refrigerator.

Thermoacoustic is science dealing with sound and thermal energy according to the thermoacoustic concept, there are two possible devices thermoacoustic prime mover and thermoacoustic refrigerator. Thermoacoustic prime mover produces acoustic work in the form of sound waves using heated gas flow. The thermoacoustic refrigerator on contrary utilizes sound waves as motive power to convey heat from lower temperature medium to higher temperature surrounding. Swift et.al [3] described the basic principle behind the thermoacoustic refrigeration. The thermoacoustic refrigerator is work on simple principle that sound wave produced by loudspeaker subjected to combine thermal oscillation and displacement oscillation, to produce thermoacoustic effect a porous structure of high heat capacity placed in resonator tube. Because of interaction between stack and working gas, a temperature gradient has created then heat transfer from one end of stack to other end and finally to the environment, similar system constructed by [4]. The thermoacoustic refrigerator comprises four components a loudspeaker, stack, resonator tube and heat exchanger. Loudspeaker produces sound waves corresponding to resonance frequency of resonator tube filled with working gas due to pressure variation working gas subjected to compression and expansion produce a thermoacoustic effect that is responsible heat conveying mechanism, heat exchanger on right-hand side Of the stack, transfer this heat to the environment. As shown in **Fig.1** the cycle start when working gas on left side cold heat exchanger at this positions the velocity of working gas is zero. When gas started moving towards stack, the velocity of gas increases with decreased in pressure and temperature. The lower temperature working gas absorb

Some heat from cold heat exchanger (CHX), along the stack spacing velocity becomes zero with rising temperature and pressure, the working gas experiences a maximum pressure at this location, as the temperature of working gas becomes more than stack temperature thus it release some amount of heat to stack.

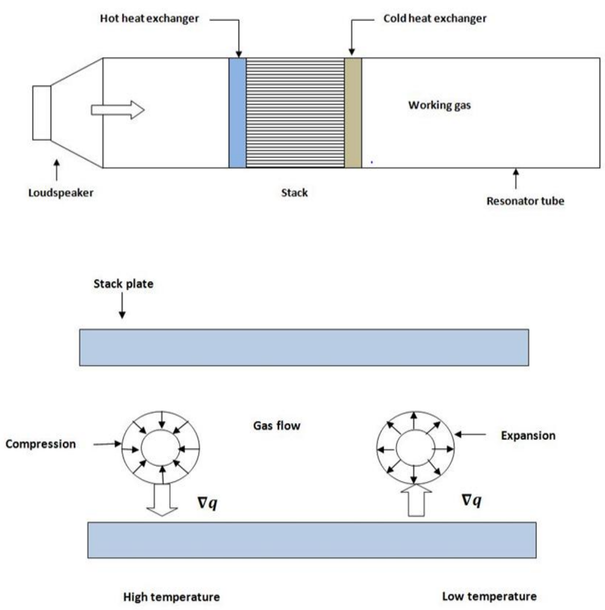

Fig 1- Thermoacoustic processes and Refrigerator [4]

The gas parcel on left side of stack absorb heat from the cold heat exchanger (CHX) and reject to stack while gas parcel on right side absorbs the heat from stack dump to hot heat exchanger (HHX). Finally, it has rejected to the surrounding.

GENERAL REVIEW

After successful flourishing TAR developed by Hofler in 1986 which had a capacity of 6- Watts, Thermoacoustic refrigeration becomes an emerging cooling technology against the conventional VCRS system without any adversarial effect on the environment However the TAR demanding the effective tuning between sound waves and resonator tube frequency, efforts are made in a diverse course to overwhelmed these issues. First commercial TAR developed by [5] with system operating pressure of 10 atm and cooling capacity of 119 Watts for ice cream sales the advancement of TAR equivalent to such system has been not reported yet.

Investigators are trying to focus on operating parameters and geometrical constraints, most of the studies concerned with the stack which essential component of thermoacoustic refrigerator due to which temperature gradient exist. It plays a vital role in producing a thermoacoustic effect, the other work related to a combination of working gas and stack material [6][7][8]. Some researchers perform numerical simulation using DELTAE, CFD, and ANSYS tool. Recently different algorithms are also used to augment the different parameters of TAR; results satisfy the objective function with slight variation in experimental results. Now a day’s researchers try to eliminate loudspeaker that is a source of acoustic waves with solar energy, waste heat from industries or power plant. This low-grade energy used to generate acoustic power the resulting TAR known as heat powered thermoacoustic refrigerator[9].The absence of moving component and use of non-hazardous inert gasses as their working fluid makes thermoacoustic refrigerator compact and reliable. Thermoacoustic refrigerator finds an application in the area of food preservation, transportation of perishable products; space operation [10]small capacity electronic equipment. The Thermoacoustic refrigeration can be a promising cooling technology in remote areas where electricity is a critical issue. A passenger vehicle can air conditioned by waste heat from the exhaust of engine [11] consider a similar system.

L.K Tarbitu [12] Considered a honeycomb structure as stack geometry with air as working gas an experiment had been carrying out with different position of square shape stack and its effect on cooling power. A position of the hot end of stack has changed and temperature variation observed for the different position of the stack. The authors try to find out the frequency variation effect on temperature gradient across the stack. They considered a quarter wavelength resonator tube with six different positions of the stack, observation has been made for decreasing distance from pressure antinode i.e. where the pressure become maximum. The analytical results were closer to the experimental result, a maximum COP observed when stack placed near the pressure antinode.

Ali Namdar .et.al [13] try to simulate input pressure using open foam package in CFD, here the maximum temperature and velocity profile has studied, and the main conclusion of this study is optimum left side heat exchanger position for enhanced performance of TAR. It was observed that with lower oscillation pressure the heat has not rejected to atmosphere via hot heat exchanger while at higher oscillation pressure the gas parcel not absorb the heat from the left side of the heat exchanger with a sharp rise in nonlinear effects.

MEH Tijani et.al[4]built a thermoacoustic cooler comprises of hot and cold heat exchanger with parallel stack geometry and helium as working gas in resonator tube. For fine-tuning between the loudspeaker frequency and frequency of resonator tube an additional mechanism introduced, an experiment performed with two different structure of stack (parallel and spiral), it reveals that parallel geometry performs better than spiral geometry. The lowest temperature of -67 ^{o} C reached with COP of 11 % that was about 20 % of Carnot COP.

J .Xu et.al[14] has presented theoretical model with numerical simulation for variation in pressure, temperature, Reynolds number and velocity of sound in working gas. The variation in temperature of left and right-hand heat exchangers with time had discussed. Initially, a temperature drop was very small but with time, variation a maximum temperature has reached on warmth region across the stack and minimum temperature in the cold region of the stack, at these condition temperature gradients was sufficient to produce the higher cooling effect with lower losses. The lower turbulence observed on cold side while hot side experiences more turbulence.

G.Allesina [15] designed and built a standing waves refrigerator with more attention on woofer box containing loudspeaker, insulation around the stack to reduce the losses . A Woofer box critically designed to reduce the sound emission behind the loudspeaker; a mechanism identical to gas spring system developed to push the gas from backside of a sound generator to front side, with a critically designed component of the system a temperature variation of 24^{o}C had achieved. The disturbance of sound waves was common when resonator tube becomes narrow.

E.C.Nsofor et.al.[16] examine the effect of operating pressure and frequency on the performance of TAR, to reduce the axial heat conduction within stack a whole resonator made by aluminum tube covered with the plastic tube. The authors had discussed the effect of a temperature gradient within the stack, with an increase in temperature gradient the cooling load increases. The main intention of this study is to optimize the operating frequency and pressure which result in higher cooling load and improved system performance. There was a certain operating range within which increase in operating pressure result in higher performance beyond this range, an adverse effect on system performance inveterate experimentally.

N.Yassen [17] modified a design strategy and built standing waves thermoacoustic refrigerator powered by solar energy. The system comprises of PV cell, stack, sound generator and two heat exchangers.The authors examined the system behavior with varying blockage ratio, a maximum temperature difference of 45 ^{o} C was observed with blockage ratio of 0.5 and for blockage ratio > 0.8 operating pressure does not influence the performance but for lower blockage ratio the impact of pressure quite notable.

Heat powered TAR is another class of thermoacoustic device; the motive power produced by thermoacoustic engine use to run the thermoacoustic refrigerator both thermoacoustic engine and refrigerator are interconnected in heat driven TAR. [9] Designed and combined a cold storage with thermoacoustic refrigerator. They have prepared and discussed a theoretical model of the system as a tool for analysis of a component of performance. An open system had considered determining the acoustic work and components efficiency through the heat flow and temperature gradient measurement.

A.Dalkiran et.al[18] analyzed the Nano scale TAR considering thermodynamic criteria, the new modified function includes work input combining with energy destruction employed for optimizing the working of the device. This modified function minimizes losses associated with entropy generation, work required to produce cooling in thermoacoustic devices. Here pressure amplitude, initial pressure, and temperature amplitude are critical parameters, with increases in pressure amplitude work input increases but COP halt.

I.Paek et.al.[19]Designed and developed a thermoacoustic cooler with main intention to study the temperature profile within resonator tube, results obtained through simulation using DELTAE simulation tool was compare with experimental results. The performance had observed for two conditions firstly supply of water to the heat exchanger and without a supply of water. He concluded that performance of TAR diminishing, as the temperature profile becomes nonlinear result in a slight decrease in system effectiveness.

R.Dragonetti et.al[20] Investigated the influence of tortuous structure on power developed inside a thermoacoustic device, thermal losses, and viscous losses because of tortuosity had discussed. The author developed a Johnson-Chamou x- allard model that required an introduction of additional five parameters rather than single hydraulic radius in case of square and circular structure. The comparison had made between the commonly used circular structure and tortuous structure. The consequence of tortuosity is adverse as it reduces thermal contact between the operational fluid and solid structure result in higher viscous losses. The working frequency and stack length are two parameters had optimized for tortuous stack structure.

COMPARATIVE REVIEW

In this study, 37 articles have reviewed dealing with experimental analysis, optimization algorithms, and methods, for improving a different aspect of TAR. The above section gives an overview regarding different aspect considered by researchers and work reported on the thermoacoustic refrigerator, which had discussed in details.

1.1 Stack

The stack is a principal component of the thermoacoustic refrigerator. The thermoacoustic effect is created along resonator tube through this porous structure; the main function of the stack is to create temperature gradient by absorbing large amount heat. The spacing between stack is determined by thermal penetration depth. It is the distance within which sound waves penetrates into working gas, these spacing should be minimum as possible so that more gas is available within this region to increase the heat interaction between working gas and stack along with an increase in heat transfer area. However, very less spacing creates pressure disturbance near the stack thus spacing limits in between $2\boldsymbol{\delta}_k$ to $4\ \boldsymbol{\delta}_k$ [21].The stack length and position are another important parameter as the power density and cooling power are function of stack length and stack position. The results of increasing stack length are positive up to certain level, with further increase in stack length there is drop in acoustic pressure and impedance which reduce the device performance.[16][22][23] found a similar results. In order to keep constant pressure and velocity over stack and to avoid acoustic wave's disturbance short stack could be better, this approximation makes $\lambda/2\boldsymbol{\pi} >> L_{stack}$. Stack center position is affects power density Swift [3] found that it should be about $\lambda/20$. Tijani [4] reveals it should be at $\lambda/8$

1.2 Stack geometry

Extensive research has been reported on stack geometry, the most frequent geometries are spiral, parallel, honeycomb and pin array later is most efficient geometry but manufacturing difficulties associated with pin array structure it is abandoned by researchers. However, pin array structure provides effective heat interaction between working gas and solid walls, the final choice base on manufacturing difficulties and conversion efficiency. The next efficient geometry to pin array is parallel plate geometry utilized by researcher's group with favorable results.**Fig.2** shows various stack geometries utilize by researcher's during their studies, spiral stack , parallel ,pin array[24] , most of the studies carried out with parallel and pin array structure.

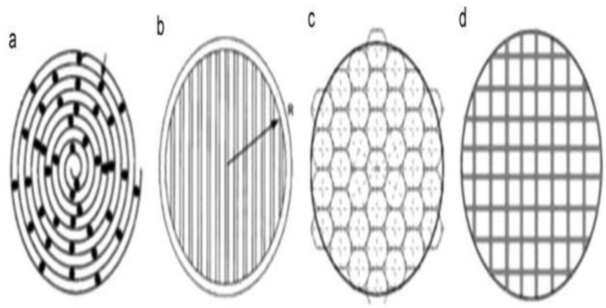

Fig 2 (a) spiral, (b) parallel, (c) honeycomb, (d) pin array [33]

1.3 Working gas

To dominate the viscous effects in thermoacoustic working gas should have lower Prandtl number, as it is the ratio of viscous effects to thermal effects, lower Prandtl number ensure that more thermal effects within the thermoacoustic device. The working gasses with a higher ratio of specific heat are favorable as the speed of sound reaches its peak. The inert gasses helium, argon, and nitrogen are promising working fluid in thermoacoustic devices as its satisfies the criteria of both higher specific heat ratio and lower Prandtl number, another advantage with inert gasses is that no hazardous effects on the environment. Amongst all inert gasses, the highest sound velocity has achieved in helium. The higher thermal conductivity of working gasses, also beneficial as it enhance heat interaction between oscillating gas within the resonator tube and stack surface results in improvement in cooling effect produced. [6] Other heavy inert gasses i.e. argon, xenon and nitrogen blended to improve the heat interaction but blending should be optimized otherwise these reduce the cooling power Tijani et.al.[25] Used a mixture of Helium-Xenon, Helium-Krypton, and Helium-Argon and Insu et. al [19] . Most of the researchers found air as working fluid for experimentation satisfying criteria of operating condition and design.

1.4 Resonator tube and Working frequency

Resonator tube is a hollow cavity within which inert gasses subjected to compression and expansion and it encloses a porous structure stack and heat exchangers. The resonator tube and loudspeaker frequency are interconnected which are used to decide the total length of the resonator cavity. For resonator tube, there are geometric length criteria depending on this criteria quarter wavelength and half wavelength is two possible resonator tube lengths. The quarter wavelength is in favor because of lower losses associated when comparing with half wavelength. Resonator tube geometry has a direct impact on cooling performance even with the absence of viscous sound effects a non-linear temperature and velocity profile creates acoustic disturbance result in poor performance hence resonator tube geometry has to optimize to get linear temperature profile. The step diameter tube has lower area comparing with single diameter tube correspondingly lower acoustic losses.

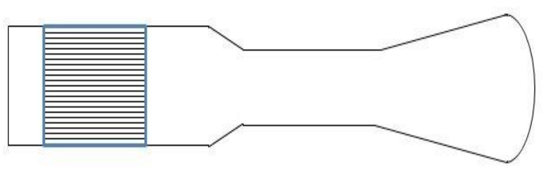

Fig 3- Hofler resonator tube [38]

Hofler et al. [38] designed a similar resonator tube with buffer volume at end of resonator tube enable better working conditions. Now a day these type of system commonly employed in TAR. The working frequency of sound waves has decided by the type of working gas and resonator cavity length along with consideration of boundary conditions. As the power density varies linearly with working frequency [26] it should be high, as possible but with an increase in working frequency stack spacing have to minimize as the working frequency and thermal penetration depth have an inverse relation. This makes stack manufacturing process difficult. For effective performance, resonance-frequency of the loudspeaker would be match with resonator tube frequency. In most of the studies, working frequency in between 300 Hz to 500 Hz [4][15][27][28][29] had selected for experimentation.

1.5 Analysis and optimization methods

Various analysis methods are continuously applied to get desired output from the thermoacoustic refrigerator, the effectiveness of thermoacoustic refrigerator expressed in terms of lowest possible temperature[4][30][31] the temperature gradient exists within the stack[32] thermoacoustic power for producing cooling [33][34]with more attention on COP of the system . The models for step diameter of resonator tube along with buffer volume at the end of resonator tube it may be spherical or conical shape, stack with different geometries and heat exchangers utilized by investigators. The validation of this type of model can be possible by numerical, analytical as well as experimental methods. DELTAEC has commonly used software for validation of experimental results, as it is best suited and specifically developed for thermoacoustic devices. The various optimization methods considering different parameters of thermoacoustic devices had applied to get the desired outcomes from the thermoacoustic refrigerator. The table gives an overview of optimization methods with their outcomes. The parameters under considerations for optimization are stack geometry, temperature gradient, the effectiveness of heat exchanger and resonance frequency, however, the efficiency of thermoacoustic refrigeration still lower than VCRS system but extensive research is going in this area to improve the performance continuously.

CONCLUSION

Different optimization methods both numerical and experimental have employed to get lower temperature along with maximum temperature gradient across the stack region, least input power for producing a cooling effect and finally the coefficient of performance of the system. Several conclusions have drawn based upon past studies in the area of thermoacoustic refrigeration.

1. Thermal penetration depth and stack spacing are critical concerns for stack geometry. The final choice will be a compromise between the manufacturing suitability and thermal penetration depth.
2. Stack position from the driver end should be critically optimize to get desired output it should place near the driver end but not exactly at driver end, the results are severe when it is placed exactly at driver end.

3. Among the stack material, Mylar is highest efficient material yet.
4. A mixture of helium and other inert gasses improves the performance their percentage can be balanced to avoid the reduction in sound velocity.

Table 1 Optimization methods

Authors	Optimization method	Parameters considered for optimization	Outcomes of optimization method
Zolpaker et.al [33]	Multi-objective genetic algorithm(MOGA)	Stack total length, the center position of the stack, drive ratio and stack plate -spacing.	Higher cooling effect and lower acoustic power at the porous structure(stack), COP 1.5 and acoustic power of 4.86 W
Picolo[35]	Second law analysis	Stack total length, center position of stack and stack plate- spacing	Minimum irreversibility, lower losses.
Sawantit et.al[36]	Multi-population GA	Stack total length and stack plate-spacing	Maximum COP 0.1753
Mawahib et.al[37]	Lagrange multiplier method	Heat exchangers(HX&CHX)	Enhanced effectiveness of HX

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