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Influence of Parallel Plate Stack Spacing on the Temperature Difference of Thermoacoustic Refrigerator by using Helium as a Working Medium

Shivakumara N V, Bheemsha Arya

Abstract: *The refrigerants are usually provided in the conventional refrigeration system despite the fact that, they produce CFCs and HCFCs, which are hazardous to the environment. However, these disadvantages can be overcome using air or inert gas in the thermoacoustic refrigeration system. The present research involves the effect of spacing of parallel plate stack on the performance of thermoacoustic refrigerator (TAR) in terms of temperature difference (ΔT). The entire resonator system as well as other structural parts of the refrigerator are fabricated by using PVC to reduce conduction heat loss. Three parallel plate stacks have been used to study the performance of TAR considering different porosity ratios by varying the gap between the parallel plates (0.28 mm, 0.33 mm and 0.38 mm). The parallel plate stacks are fabricated by using aluminium and mylar sheet material and the working fluid used for the experimental study is helium. The experiments have been carried out with different drive ratios ranging from 0.6% to 1.6% with operating frequencies of 200 – 600 Hz. Also the mean operating pressure used for the experiment is 2 to 10 bar and cooling load of 2 to 10W are considered. The ΔT between the hot heat exchanger and cold heat exchanger is recorded using RTDs and Bruel and Kjaer data acquisition system. Experimental results shows that the lowest temperature measured at cold heat exchanger is -2.1 ^{o}C by maintaining the hot heat exchanger temperature at about 32 ^{o}C. The maximum temperature difference of 32.90 ^{o}C is achieved.*

Keywords: ***Thermoacoustic Refrigeration, Temperature difference, Parallel Plate Stack, Drive Ratio, Porosity Ratio.***

I. INTRODUCTION

In the current century, environmental issues have become a key concern in the design, development and manufacturing of refrigeration, heat pump and air conditioning systems. The existing refrigerators are operated by using hazardous refrigerants, which developes CFCs and HCFCs resulting in the depletion of ozone layer. Hence, it is necessary to develop a viable alternate refrigeration system which is free from usage of dangerous chemicals and refrigerants. The thermoacoustic refrigeration system is a new alternate cooling technology which is eco-friendly. Thermoacoustic refrigeration system offers a revolutionary solution for the current problem of energy consumption and environmental pollution with merits of environmental safety, simplicity, higher reliability and lower manufacturing cost. Further, as the TAR has no moving parts, the life of the components increases significantly. The phenomenon of thermoacoustics was first observed and studied in the year 1777 by Higgins [1] who made the first observation and investigation of organ pipe type oscillations by appropriately positioning hydrogen flame inside the open ended tube. During 19th century Soundhauss [2] performed an experiment on a hollow glass tube with one end open and other end closed (Soundhauss tube), in which the sound waves are generated by maintaining the closed end very hot. In the year 1859 Rijke [3] showed in his study that strong oscillations can be produced when a heated wire screen is placed at the lower end of the open ended pipe, named as Rijke tube. Rott et al., [4] carried out analytical and theoretical work on thermoacoustic refrigerators and heat pumps.

Though the phenomenon of thermoacoustics was discovered more than a century ago, substantial amount of research work in this area was actually started at the LAN (Los Alamos National) laboratories only about 35 years ago by the scientists Swift et al., [5,6]. They developed different kinds of thermoacoustic refrigerators and heat engines. Merkli and Thomson [7, 8] as well as Hofler [9] made a number of attempts for the development of thermoacoustic devices for practical cooling applications. Wetzel and Herman [10] reported a research work on design optimization of TAR by short stack boundary layer approximation technique. Tijani et al., [11] have reported theoretical design, development and performance analysis of TAR by considering the theory of linear thermoacoustics for a cooling load of 4W, contained in a vacuum vessel for different gases as well as gas mixtures. They have explained the description of the design, detailed construction of each part of the refrigerator and the procedure for preparing the gas mixtures. A low temperature of – 65 ^{o}C for the COP of 1.06 was reported at the cold heat exchanger which is the lowest temperature reported till now.

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* Correspondence Author
Shivakumara N V*, Department of Mechanical Engineering, BMS College of Engineering, Bengaluru-560 019, Karnataka, India
Email: shivu2k4@gmail.com, shivakumara@bmsce.ac.in
Dr.Bheemsha Arya, Department of Mechanical Engineering, BMS College of Engineering, Bengaluru-560 019, Karnataka, India
Email: arya.mech@bmsce.ac.in

They also studied the effect of different thermoacoustic properties such as stack plate spacing and prandtl number on the performance of TAR. Akhavanbazaz et al.,[12] investigated the obstruction of gas on the TAR performance for different cases and reported that the obstructions in the stack and heat exchanger area have significant effect on the TAR performance. They have also suggested that the optimization of theses parameters are very much necessary to enhance the performance of thermoacoustic devices. Tasnim et al.,[13] examined the effects of various working fluids and operating conditions on the performance of TAR. In their study, they have considered different operating conditions such as stack plate spacing (y_0), mean pressure (p_m), and drive ratio to examine the influence of working fluid by varying the Prandtl number (Pr) from 0.28 to 0.7. Bheemsha et al., [14] have designed and fabricated 10W cooling load TAR for two working fluids of helium and air for an operating pressure up to 10 bar. They optimized the COP of stack and reported a value of 2.5. Prashantha et al., [15,16] designed and optimized the loud speaker driven 10W cooling power TAR for a ΔT of 120K using linear thermoacoustic theory and also explained the theoretical design procedure for optimizing the resonator. The same model is simulated by using DeltaEC which estimates –47 ^{o}C and –48 ^{o}C are the lowest temperatures for the convergent-divergent and hemispherical resonator designs respectively. Nayak B et al.,[17] outlined the effect of stack geometry by considering various operating conditions on the TAR performance for four different types of stacks i.e. parallel plate stack of 0.33 mm gap and 3 circular stacks of 1 mm, 2 mm and 3 mm diameter. They conducted experiments and recorded the ΔT of 19.4 ^{o}C for parallel plate stack with helium as working fluid. They also concluded that the parallel plate stacks are able to create more temperature difference compared with circular stacks. Bheemsha et al., [18] have studied the effect of dynamic pressure on the TAR performance for different operating conditions. The experimental setup was fabricated by using aluminum with 2 mm polyurethane coating inside the resonator to reduce the heat losses. Elnegiry et al.,[19] studied the standing wave loudspeaker driven thermoacoustic heat pump for optimization using DeltaEC software and simulated to identify and optimizing operating conditions.

Study of the literature reveals that many researchers have worked on the performance of thermoacoustic refrigerators numerically as well as theoretically. On the contrary, a very limited amount of work has been carried out experimentally. However, most of these experimental works were carried out by fabricating Aluminium and other metallic resonator system resulting conduction heat losses. Hence, it is very important to conduct a detailed experimental study by constructing components of TAR by different materials which are having less thermal conductivity thereby enhancement in the performance can be achieved. In the present experimental investigation, the components of TAR are fabricated using PVC material in order to study the effect of various parameters such as operating pressure, operating frequency, cooling load and drive ratios on the TAR performance in terms of ΔT and hence becomes the subject of present investigation.

II. PRINCIPLE AND CONSTRUCTION

Principle: TAR consists of electro-dynamic acoustic driver (speaker), resonator, hot and cold heat exchangers, stack and working medium. TAR uses air and other inert gases like helium, neon, argon, etc. as refrigerants which have no negative impact on the components of the refrigerator as well as on the atmosphere. The sound waves produced by the electroacoustic driver develops pressure waves. These pressure waves in turn results in the compression and expansion of gas particles. Thus ΔT is created between the two ends of the stack. This difference in temperature can be harnessed by implementing heat exchangers and thermocouples on either side of the stack. The number of thermocouples and also the location of thermocouples play an important role in the measurement of ΔT. In a brief, a thermoacoustics is the study of the conversion of sound energy to heat energy by collision of molecules, which in turn produces disturbance in the working gas environment, where it creates destructive and constructive interfaces. The gas molecules within the stack spacing heats-up due to compression of constructive interfaces and cools down due to expansion of destructive interfaces. This is the basic principle of thermoacoustic refrigeration system.

Construction: A thermoacoustic refrigerator comprises of stack, resonator, loud speaker and heat exchangers (hot & cold) as shown in Fig.1.

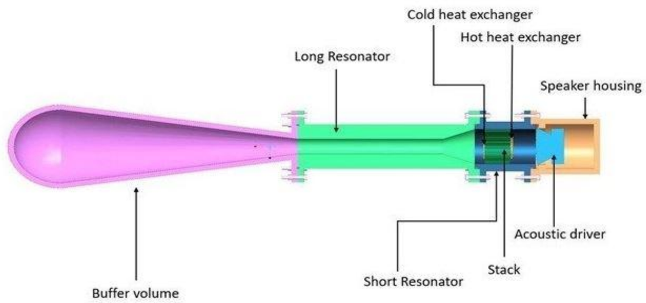

Fig.1: Cross-sectional view of Thermoacoustic Refrigerator modeled in Pro-E.

A stack is the heart of TAR which transfers heat from one end to the other by a pumping action inside the closed resonator tube which has an inert gas environment. Copper tube heat exchangers are employed at both ends of the stack. The hot and cold heat exchangers are built with 3.866 mm and 1.933 mm hollow copper tubes as shown in Fig. (2) and Fig. (3) respectively.

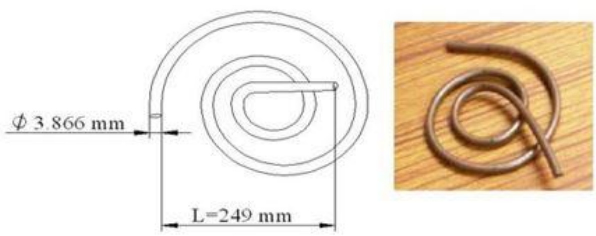

Fig.2: Hot heat exchanger details.

Both heat exchangers are covered with two copper wire mesh of 0.6 mm thickness with porosity ratio of about 75%, which helps to enhance the rate of heat transfer. The TAR is designed and constructed for a cooling load of 10W using pure as the working fluid.

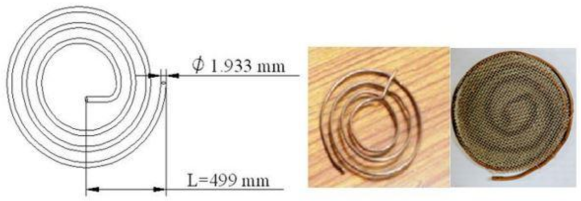

Fig.3: Cold heat exchanger details with copper mesh attached at both sides

Varieties of stack geometries such as parallel plate stack, circular stack, honeycomb structured, spiral stack, etc. have been used by many researchers to evaluate the performance characteristics. Parallel plate stack gives better performance compared to all other stack geometries [17]. In this study, aluminum sleeves and mylar sheet material are used to fabricate the parallel plate stack to study the effect of spacing on the performance of TAR. The schematic representation of the parallel plate stack is shown in Fig.4.

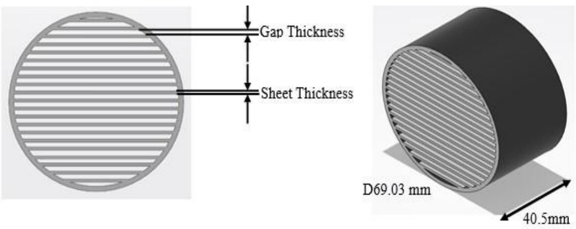

Fig.2: Parallel plate stack schematic representation

Aluminum sleeves are machined with OD 69.03 mm, ID 65.03 mm for a length of 40.5 mm.

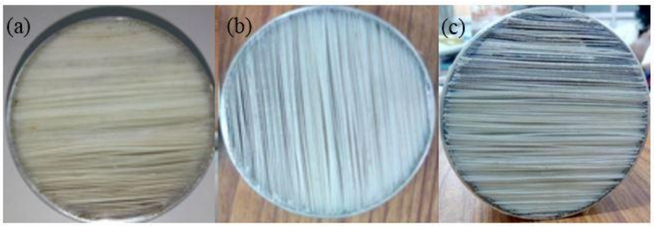

Fig.3: Parallel Plate Stacks: (a) 0.28 mm gap, (b) 0.33 mm gap (c) 0.38 mm gap

Mylar sheets are sheared to the required dimension and inserted in to the slots of aluminum sleeves created by using wire EDM with 0.12 mm diameter. Different gaps of 0.28 mm, 0.33 mm and 0.38 mm are maintained between the two successive mylar sheets for preparing three parallel plate stacks as shown in Fig.5.

III. EXPERIMENTAL SETUP

Structural components of TAR including resonator are constructed using PVC due to its insulating character and ease of manufacturing. The overall experimental setup having data acquisition system, helium cylinder, temperature sensors and other components with connections is as shown in Fig.6. The hot heat exchanger is provided with cooling water connections to remove excess heat and to maintain the hot heat exchanger temperature closer to atmospheric temperature of about 32 ^{o}C. An electric heater of about 10W capacity is placed on the cold heat exchanger for cooling power measurement, which is operated by 5A/30V DC power supply unit. A variable power acoustic driver of input 0 – 120W, 8X is selected with an audio generator and amplifier to produce required frequency of 100 – 600 Hz. Cooling water circulation is provided to acoustic driver in order to remove excess heat, which is generated due to continuous operation of loudspeaker inside the closed resonator housing.

Fig.4: Experimental Setup of Thermoacoustic Refrigerator

Two pressure transducers PCB Piezotronics (Voltage sensitivity 0.00146 mV/ Pa) are placed, one in the buffer volume section to measure the operating pressure of working fluid and other one near the driver end to measure the dynamic pressure of the acoustic driver. A Bourdon tube pressure gauge in the range 0 – 30 bar is installed in the buffer volume section to measure and verify the actual pressure of working fluid available inside the TAR. Pressure transducers and pressure gauge are attached with threads and sealing rings. Four Heatcon RTD PT 100 temperature sensors of thickness 2 mm, 2 m long with 15 mm diameter is operating in the temperature range –100 ^{o}C to +100 ^{o}C are attached on the cold and hot heat exchangers. The data acquisition system and function generator are used to record temperature variations and amplify the output signals respectively. The temperature and pressure sensors are checked and verified for their functionality and calibrated by certified suppliers for proper functioning. The complete setup of thermoacoustic refrigerator and joints are checked for leakage and tested for pressure upto 12 bar.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Three parallel plate stacks with different porosity ratio in terms of spacing between the two successive plates are considered for the experimental study with helium as a working fluid. The experiments are conducted for three drive ratios of 0.6%, 1.0% and 1.6 % with 5 different cooling loads of 2W to 10W. Also operating pressures of 2 bar to 10 bar with an increment of 2 bar is used in the experimental study. The experimental results are presented and discussed in the subsequent sub-headings.

A. Effect of Operating Frequency on the Performance of TAR for 2W Cooling Load at 2 bar Operating Pressure

The variation of temperature difference vs. operating frequency for different drive ratios have been illustrated in Figs 7 (a) – 7 (c) for a constant operating pressure (2 bar) and a constant cooling load (2W).

It is observed from Fig.7 (a) that the ΔT increases with the increase in frequency upto 400Hz and thereafter decreases with the further increase in operating frequency. It may be attributed to the fact that the influence of thermal penetration depth (δk) across the stack decreases when the operating frequency increases beyond 400 Hz. This behaviour is almost similar for all other drive ratios, which can be seen in Figs 7 (b) and 7 (c). It is also observed from Figs 7 (a) – 7 (c) that the ΔT increases with the increase in drive ratios. It is worth to mention that for a given parallel plate stack, the ΔT increases with the decrease in gap between two successive plates irrespective of drive ratios. It is found that for a stack of 0.28 mm gap with a drive ratio 1.6% gives highest ΔT as compared to all other cases which can be seen in Fig. 7 (c).

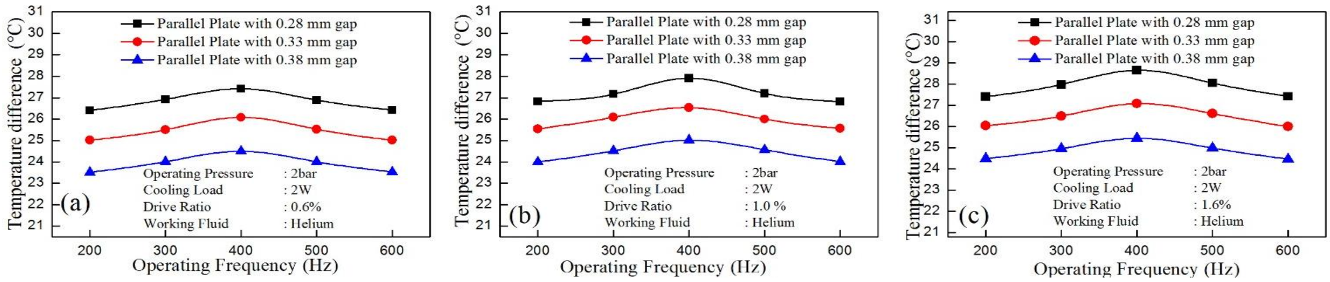

Fig.5: Variation of ΔT with operating frequency for 2 bar operating pressure at 2W cooling load for three parallel plate stack geometries by considering different drive ratios of: (a) 0.6 % (b) 1.0 % and (c) 1.6 %.

B. Effect of Operating Frequency on the Performance of TAR for 10W Cooling Load at 2 bar Operating Pressure

The effect of spacing between the plates and operating frequency on ΔT has been studied for different drive ratios with 10W cooling load at a constant operating pressure of 2 bar as can be seen in Figs 8 (a) – 8 (c).

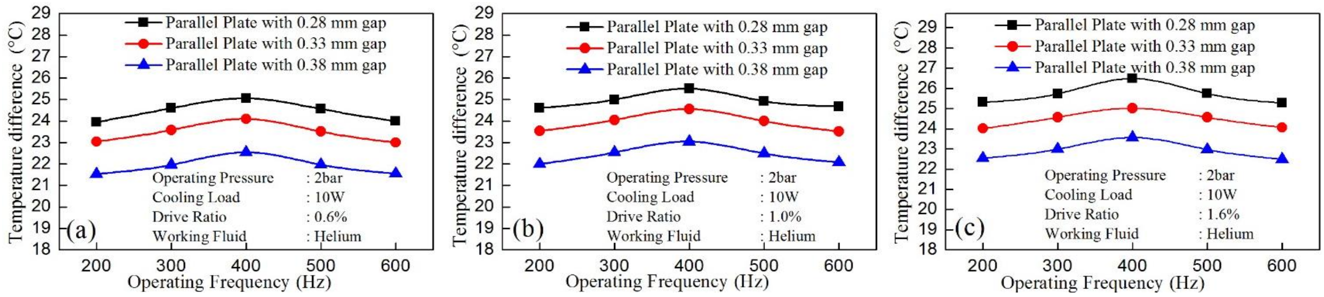

Fig.6: Disparity of ΔT against operating frequency for 2 bar constant operating pressure at 10W cooling load for three parallel plate stack geometries by considering three different drive ratios: (a) 0.6 % (b) 1.0 % (c) 1.6 %.

From Figs 8 (a) – 8 (c) it can be observed that the ΔT vs. operating frequency characteristics are almost similar to that of 2W cooling load which is depicted in detail in section IV.A except that magnitude of ΔT is less as compared to 2W. This may be attributed to the fact that the electro acoustic power is not sufficient to drive the heat from cold side of the stack to the hot side at higher cooling loads. It is also observed from Figs 8 (a) – 8 (c) that the ΔT increases as the drive ratio increases from 0.6 % to 1.6 % irrespective of spacing and operating frequency. The significant numerical results are tabulated in table 1 and table 2.

Table 1: Summary of results for the stack of 0.28 mm gap at 2 bar operating pressure for 2W – 10W cooling loads.

Cooling load (W)	Drive ratio (%)	Frequency (Hz)	T_h (°C)	T_c (°C)	ΔT (°C)	Cooling load (W)	Drive ratio (%)	Frequency (Hz)	T_h (°C)	T_c (°C)	ΔT (°C)
2	0.60	400	31.22	3.80	27.42	8	0.60	400	31.18	5.20	25.98
2	1.03	400	31.30	3.39	27.91	8	1.10	400	31.37	4.90	26.47
2	1.61	400	31.52	2.87	28.65	8	1.67	400	31.34	4.49	26.86
4	0.60	400	31.34	4.49	26.84	10	0.61	400	31.91	6.85	25.06
4	1.13	400	31.34	3.80	27.54	10	1.10	400	31.24	5.73	25.51
4	1.62	400	31.13	3.50	27.63	10	1.67	400	31.59	5.10	26.49

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Table 2 : Consolidated numerical results for the stack at 2 bar operating pressure with 400 Hz Operating frequency for parallel plate stack with spacing (a) 0.33 mm (b) 0.38 mm.

(a) 0.33 mm gap					(b) 0.38 mm gap				
Cooling load (W)	Drive ratio (%)	Th (°C)	Tc (°C)	ΔT (°C)	Cooling load (W)	Drive ratio (%)	Th (°C)	Tc (°C)	ΔT (°C)
2	0.61	31.84	5.76	26.08	2	0.61	31.25	6.75	24.50
2	1.11	32.56	6.02	26.54	2	1.00	31.57	6.55	25.02
2	1.67	32.43	5.35	27.08	2	1.60	31.92	6.17	25.75
4	0.61	31.41	5.85	25.56	4	0.60	31.44	7.42	24.02
4	1.10	33.08	7.06	26.02	4	1.10	31.92	6.99	24.93
4	1.67	32.42	5.85	26.57	4	1.62	31.54	6.53	25.02
6	0.61	32.46	7.44	25.02	6	0.62	31.62	8.11	23.51
6	1.10	32.81	7.25	25.56	6	1.09	31.26	7.25	24.01
6	1.67	32.49	6.41	26.08	6	1.66	31.21	6.70	24.51
8	0.60	32.56	8.02	24.54	8	0.64	31.31	8.30	23.01
8	1.10	32.76	7.75	25.01	8	0.99	31.41	7.88	23.53
8	1.67	32.92	7.40	25.52	8	1.60	31.26	7.19	24.07
10	0.61	31.86	7.76	24.10	10	0.62	31.23	8.69	22.54
10	1.10	32.86	8.31	24.55	10	1.11	31.21	8.17	23.04
10	1.67	32.34	7.33	25.02	10	1.64	31.11	7.54	23.57

C. Effect of Operating Frequency on the Performance of TAR for a Cooling Load of 2W at 10 bar Operating Pressure

The effect of operating frequency, drive ratio and spacing between the plates on the performance of TAR at 10 bar operating pressure for a cooling load of 2W are plotted in Figs 9 (a) – 9 (c).

ΔT follows the upward trend as the operating frequency increases for all the drive ratios as well as different spaced stacks till 400 Hz and thereafter it follow the downward trend irrespective of any operating conditions. The stack with 0.28 mm spacing is capable of producing a temperature difference of 32.9 °C whereas the stacks with 0.33 mm and 0.38 mm spaced stacks are capable of producing 30.75 °C and 29.58 °C respectively. The above said values of ΔT are achieved for a drive ratio of 1.6 % for all three stacks. Hence it is obvious that conducting experiments at higher drive ratios gives better results. However higher drive ratios leads to more noise due to the continuous operation of loudspeaker. It is worthwhile to note that the ΔT values are significantly higher for 10 bar operating pressure, 2W cooling load and 1.6 % drive ratio compared to any other operating parameters.

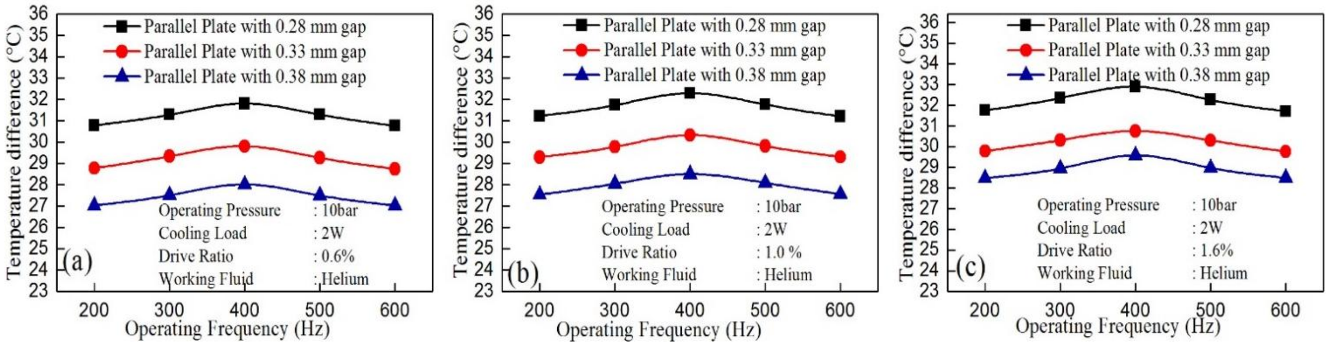

Fig.7 : Disparity of ΔT with operating frequency with drive ratios of (a) 0.6% (b) 1.0% & (c)1.6%) at 2W cooling load

D. Effect of Operating Frequency on TAR Performance for 4W – 10W Cooling Loads at 10 bar Operating Pressure

The influence of drive ratio, cooling load and stack spacing has been studied for different cooling loads (4W – 10W) which can be seen in Figs 10 (a) – 10 (d) for a constant mean operating pressure of 10 bar. In this set of experiments, the operating pressure has been kept constant (10 bar) by varying the cooling load and drive ratio. The graphs are plotted by combining the effect of all three drive ratios for 4W, 6W, 8W and 10W cooling loads. It can be observed from Figs 10 (a) – 10 (d) that the performance of TAR in terms of ΔT has an inverse effect over the cooling load, i.e. the magnitude of ΔT goes on decreasing as the cooling load increases from 4W to 10W. The significance of the above trend is due to the insufficient electro acoustic energy because of the low efficiency of acoustic driver (16.125%) at higher cooling loads. The important findings are tabulated in table 3.

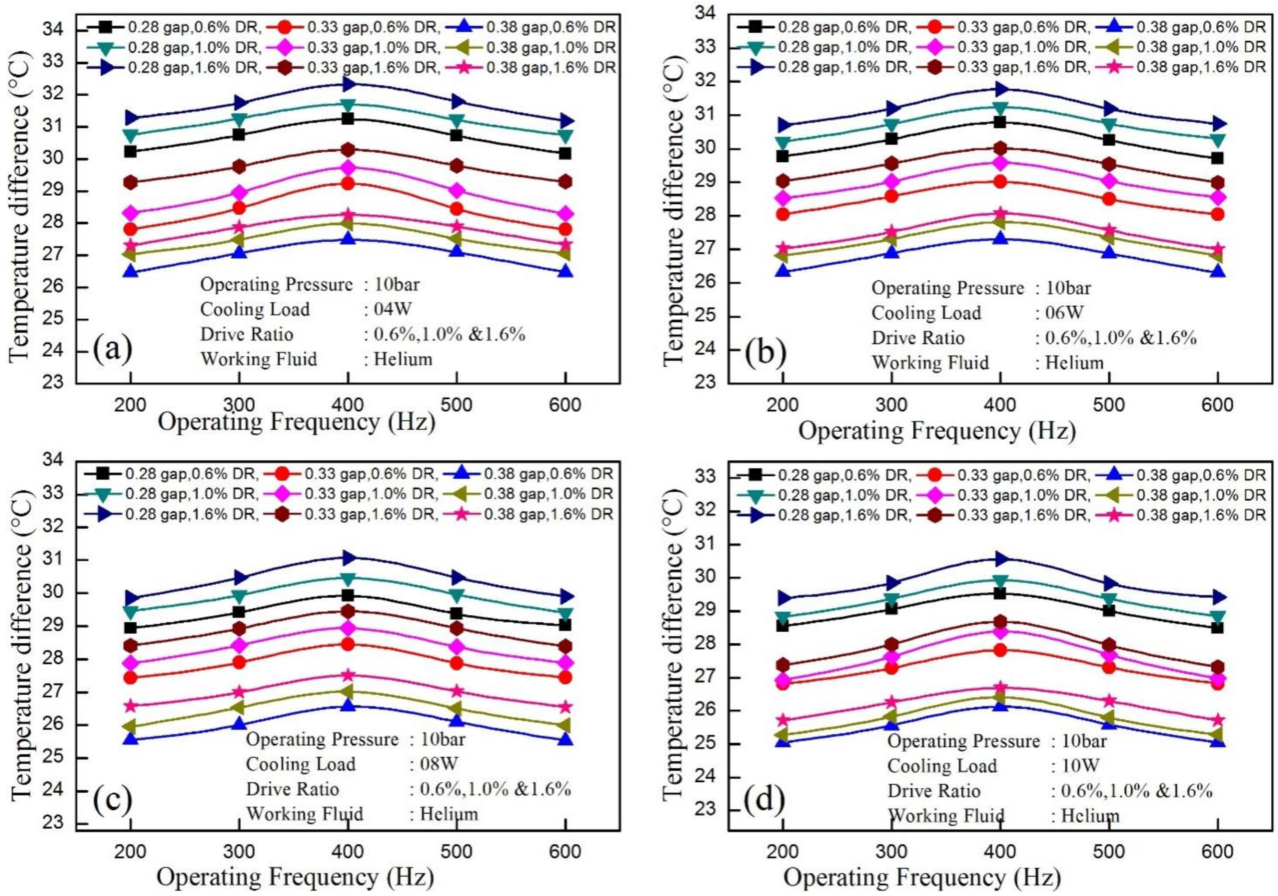

Fig.8: Variation of ΔT with operating frequency for different drive ratios (0.6%, 1.0% & 1.6%) by considering four different cooling loads: (a) 4W (b) 6W (c) 8W and (d) 10W

Table 3: The overview of important results with 10 bar operating pressure for 400 Hz frequency at 1.6% drive ratio with spacing of: (a) 0.28 mm, (b) 0.33 mm, and (c) 0.38 mm.

(a) 0.28 mm gap				(b) 0.33 mm gap				(c) 0.38 mm gap			
Cooling load (W)	T_h (°C)	T_c (°C)	ΔT (°C)	Cooling load (W)	T_h (°C)	T_c (°C)	ΔT (°C)	Cooling load (W)	T_h (°C)	T_c (°C)	ΔT (°C)
2	30.80	-2.10	32.90	2	33.12	2.75	30.75	2	31.53	1.95	29.58
4	31.19	-1.14	32.33	4	33.29	3.00	30.29	4	31.33	3.08	28.25
6	31.29	-0.48	31.77	6	32.89	2.87	30.02	6	31.44	3.36	28.08
8	31.49	0.42	31.07	8	33.01	3.56	29.45	8	31.54	4.04	27.51
10	31.27	0.71	30.56	10	33.47	4.19	29.29	10	31.52	4.83	26.70

E. Cooling Load vs. Temperature Difference for 2 bar Mean Operating Pressure at 400 Hz Operating Frequency.

The impact of cooling load and other operating parameters on the value of ΔT has been studied for a particular pressure of 2 bar and 400 Hz operating frequency which can be seen in Figs 11 (a) – 11 (c) by considering three different drive ratios. It is observed from Fig.11 (a) that the ΔT is a function of cooling load, as the cooling load increases the ΔT decreases, i.e., ΔT of higher value is achieved for lower value of cooling load. For 2W cooling load, the ΔT is higher because the required acoustic power is adequate to take away the heat developed in the stack whereas the ΔT is lowest for 10W cooling load as the required acoustic power is not sufficient to remove heat. A very similar behavior can also be seen for higher drive ratios, which can be observed in Fig.11 (b) and Fig.11 (c). The numerical variation of ΔT against the cooling loads for 2 bar operating pressure are shown in detail in table 1 and table 2.

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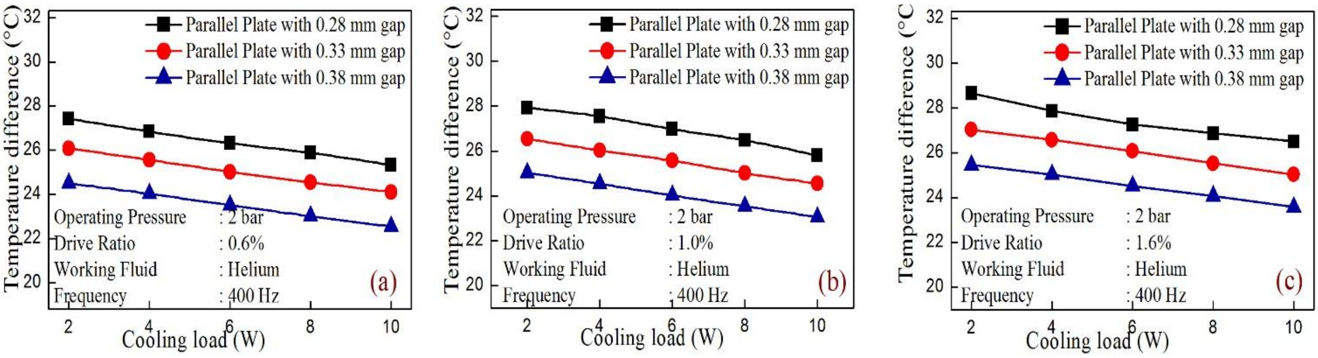

Fig.9: Variation of temperature difference against cooling loads for three parallel plate stack geometries at 2 bar mean operating pressure at 400 Hz frequency with drive ratios of: a) 0.6%, (b) 1.0% and (c) 1.6%.

F. Cooling Load vs. Temperature Difference for 10 bar Mean Operating Pressure at 400 Hz Operating Frequency.

The effect of porosity and drive ratio on the ΔT for any particular cooling load can be seen in Figs 12 (a) –12 (c) at 10 bar operating pressure.

The effect of 10 bar operating pressure on the performance of TAR in terms of ΔT for various operating parameters are almost similar to that of 2 bar operating pressure [Figs 11 (a) – (c)] except for a higher magnitude of ΔT which can be seen in Figs 12 (a) – 12 (c). It is worth mentioning that for a stack of 0.28 mm gap with a drive ratio 1.6% gives the highest ΔT as compared to all other operating conditions, which can be seen in Fig. 12 (c).

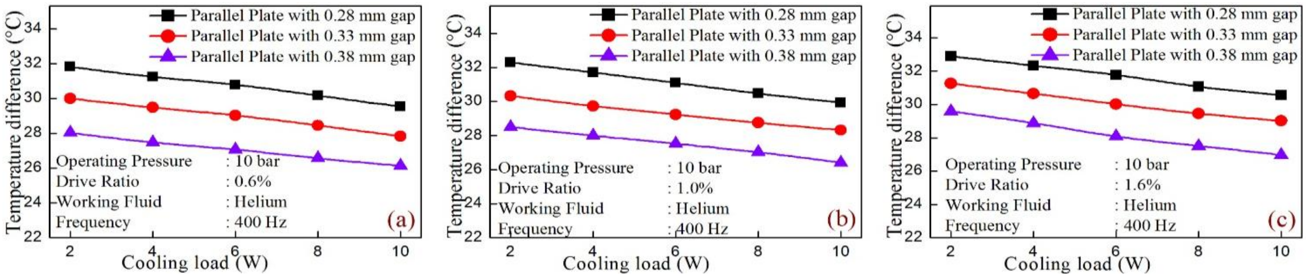

Fig.10: Deviation in ΔT with respect to cooling loads applied to three parallel plate stacks for a mean operating pressure of 10 bar having a) 0.6%, (b) 1.0% and (c) 1.6% drive ratios at constant operating frequency of 400 Hz.

G. Effect of Mean Operating Pressure on the Performance of TAR in terms of ΔT at 2W and 10W cooling loads.

The mean operating pressure is one of the very important operating parameter in the experimental study of TAR. It is evident from the previous studies as well as previous subsections that, the enhanced performance can be achieved when the TAR operates at higher pressures. As the operating pressure acts as a heat carrying mechanism and higher pressure results in larger buckets which accelerates the heat transfer process. Considering the above said reasons the study has been conducted to evaluate the TAR performance by varying the mean operating pressure from 2 bar to 10 bar with a step size of 2 bar and the results are presented.

The disparity of ΔT with respect to mean operating pressure at 400 Hz operating frequency and with different drive ratios of (a) 0.6% (b) 1.0% and (c) 1.6% for a cooling loads of 2W and 10W are depicted in Figs 13 {(a) – (c)} and 14 {(a) – (c)} respectively.

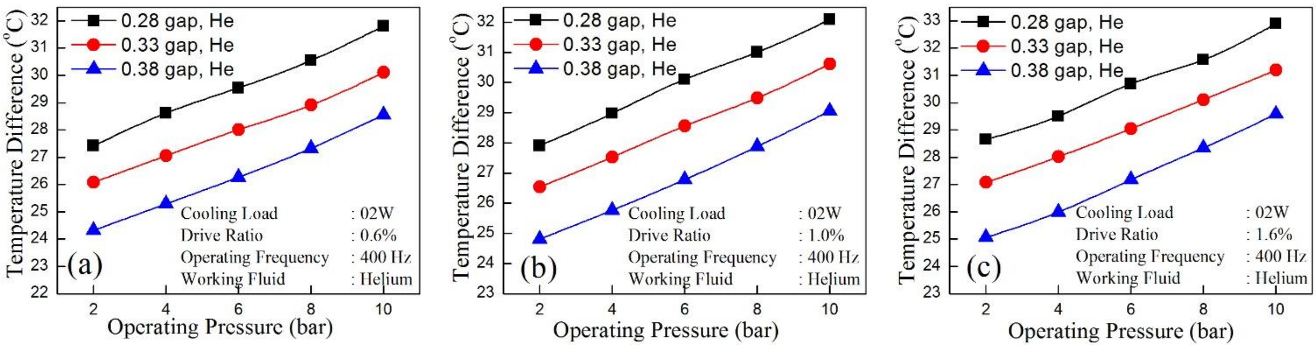

Fig.11: Variation of ΔT with mean operating pressure for 2W cooling load at 400 Hz operating frequency with drive ratios of: (a) 0.6% (b) 1.0 % and (c) 1.6%.

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From Fig. 13 (a) it is clearly visible that the performance of TAR is increasing as the pressure advances from 2 bar to 4 bar, 4 bar to 6 bar, 6 bar to 8 bar and 8 bar to 10 bar without changing other test parameters, that is keeping drive ratio, operating frequency and cooling load constant. The stack porosity has an impact over the TAR performance, that is the stack with less porosity ratio (0.28 mm spacing) performs relatively better as compared with the stacks of higher porosity ratios (stacks of 0.33 mm and 0.38 mm spaced stacks).

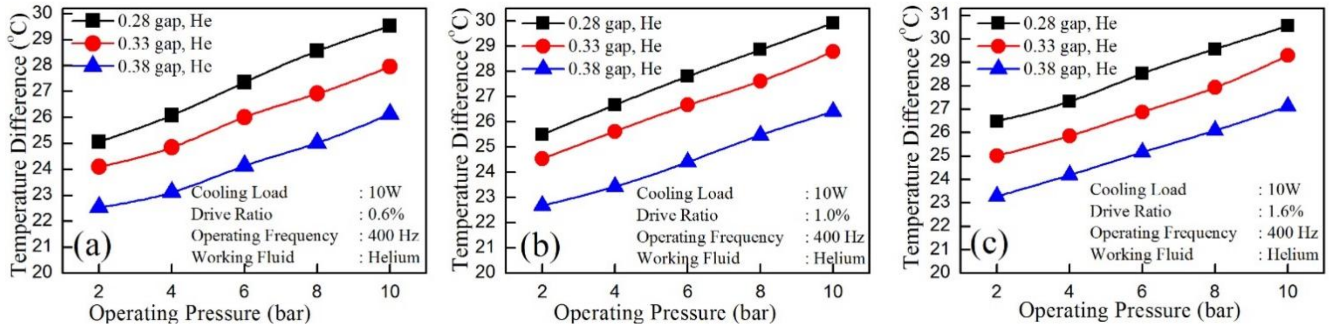

Fig.12: Variation of ∆T with mean operating pressure for 10W cooling load at 400 Hz operating frequency with drive ratios of: (a) 0.6% (b) 1.0 % and (c) 1.6%.

V. CONCLUSION

To study the performance of TAR in terms of ∆T to investigate the influence of porosity ratio in terms of stack spacing by considering different operating conditions with helium as a working fluid are carried out. The outcomes of the experimental study are as follows:

- The experimental results indicate that the ∆T between cold and hot ends of the stack is greater at 2W cooling load and lesser at 10W cooling load at any operating frequency.
- The maximum temperature differences of 32.90 °C, 30.75 °C and 27.58°C are achieved for 0.28 mm, 0.33 mm and 0.38 mm spaced parallel plate stacks respectively for a particular mean operating pressure of 10 bar, cooling load of 2W with drive ratio of 1.6% at an operating frequency of 400 Hz
- The lowest temperature of -2.1°C is achieved at the cold heat exchanger for 0.28 mm spaced stack for 10 bar operating pressure at 400 Hz of operating frequency with 1.6 % drive ratio and 2W cooling load.
- The ∆T of the parallel plate stack with 0.28 mm space is better compared to other two stack geometries.

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AUTHORS PROFILE

Shivakumara N V is a Senior Grade Lecturer in the Department of Technical Education, Government of Karnataka. Currently Pursuing his Ph.D (Full-Time) in the Department of Mechanical Engineering, B.M.S College of Engineering, Bengaluru, Karnataka, India. He graduated from PES Institute of Technology (PESIT), Bengaluru in 2008. He has worked in the R&D of WABCO-TVS and RBEI (Robert Bosch Engineering and Business Solutions) for three years. He has obtained his Masters in Thermal Power Engineering from Siddaganga Institute of Technology (SIT), Tumakuru, Karnataka, in 2015. He also has 8 years of teaching experience in the Department of Technical Education, Government of Karnataka. His research areas are Thermoacoustic refrigeration, IC engines and alternate fuels. He has a credit of publishing papers in an international conferences and journals.

Dr.Bheemsha Arya is a Professor and Principal in BMS Evening College of Engineering, Bengaluru, Karnataka, India. He has received B.E degree in Industrial and Production Engineering from Bangalore University, Further studied in Mechanical Engineering and received M.E degree (Manufacturing Science and Engineering) from U.V.C.E. Bengaluru, Karnataka, India. He received Ph.D. from Visveswaraya Technological University, Belgaum, Karnataka India. He served has a Head of the department in the department of Mechanical Engineering in BMSCE. He has an industrial experience of 7 years followed by 16 years of teaching experience. His research interests are heat transfer enhancement, Thermoacoustic refrigeration system, heat exchangers, pressure sensors, Composite Materials. Published many papers in various national, international journals and conferences.