

# Effect of parallel plate stack spacing on the performance of thermoacoustic refrigerator in terms of temperature difference using air as a working fluid

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**Abstract:** The existing conventional refrigerators are operated by using hazardous refrigerants, which produces CFCs and HCFCs resulting in the depletion of the ozone layer. However, these disadvantages can be overcome using inert gases in the thermoacoustic refrigeration system. The present research involves the effect of the spacing of a parallel plate stack on the performance of the thermoacoustic refrigerator (TAR). TAR is fabricated by using Poly-Vinyl-Chloride (PVC), which is designed for 10W cooling power. 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 zero air. 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 the cooling load of 2 to 10W is considered. The temperature difference ( $\Delta T$ ) between the hot heat exchanger and cold heat exchanger is recorded using RTDs and Bruel and Kjaer data acquisition system. Experimental results show that the lowest temperature measured at cold heat exchanger is 1.23 °C by maintaining the hot heat exchanger temperature at about 32 °C. The maximum  $\Delta T$  of 30.77 °C is achieved.

## 1. Introduction

Most of the conventional refrigerators mainly depend on the pumps and refrigerants for the transfer of heat and to achieve the necessary cooling effect. The refrigerants which are widely used in the conventional refrigeration system are hazardous in behaviour with the end product of Hydrochlorofluorocarbons (HCFCs) and Chlorofluorocarbons (CFCs). The significant effect of these gases is greenhouse emission, which causes damage to the ozone layer. In order to tackle these problems, it is necessary to develop environment-friendly alternative refrigeration to conventional refrigeration systems such as evaporative refrigeration, steam jet refrigeration, dry ice refrigeration, thermoelectric refrigeration, thermoacoustic refrigeration system, etc., which are free from hazardous refrigerants and chemicals. Among these non-conventional refrigeration systems, thermoacoustic refrigeration is a viable alternative for the existing conventional refrigeration. It utilizes the power of acoustic waves in an air or inert gas atmosphere to generate the required pressure waves which compress and expand the



gas particles within the closed resonator tube. It is also important to notice that TAR has no moving parts as such the life of the components increases significantly. As the TAR is independent of mechanical moving parts and uses no hazardous refrigerants, the greenhouse emissions are eliminated. Thus the working environment remains clean. Thermoacoustics is the study of the conversion of sound energy to heat energy by collisions of molecules, which in turn produce a 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 the expansion of destructive interfaces. This is the basic principle of the thermoacoustic refrigeration system. TAR is constructed by using heat exchangers, speaker or acoustic driver, resonator and a stack along with an atmosphere of inert gases (Helium, Argon, Neon, Xenon, Air, etc.).

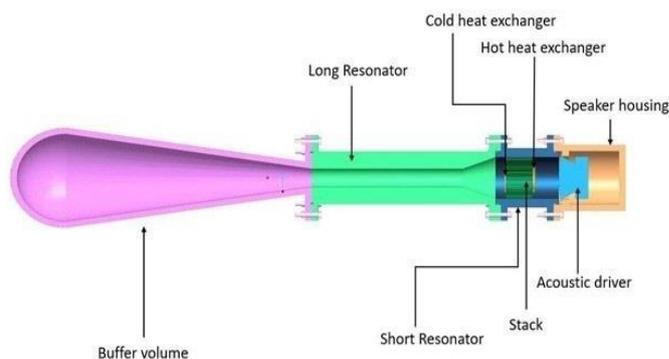
The discovery of the phenomenon of thermoacoustics was started more than a century ago. However, a substantial amount of research work in this area was started at the LAN (Los Alamos National) laboratories only about 35 years ago by the scientist named Swift and his team. They developed different kinds of thermoacoustic refrigerators and heat engines [1][2]. In the 19th century, Soundhauss explained an effect called ‘‘Glowing glass harmonica’’ in which glass blowers witnessed that hot glass bulbs which are attached to cool stems would sing occasionally. This started an investigation which lasted 40 years. Rott et al., [3] worked on solid quantitative thermoacoustics, in which intelligent thermoacoustic engine designs were created. Merkli et al., [4] made several attempts and initiated the development of thermoacoustic devices for different real-world practical applications of cooling and heating. Wetzel and Herman [5] reported a research work on design optimization of TAR by short stack boundary layer approximation technique. Minner et al., [6] described the heat exchanger formation and choice of working fluid. Knio O M and Worlikar A S [7] performed numerical studies for adiabatic unsteady flow all over the stack on a thermoacoustic refrigeration system. Belcher et al., [8] studied the suitability of working gases for thermoacoustic cooling and heating applications and reported the desirable characteristics of suitable working gases. Garret et al., [9] developed the TAR for the application of space crafts, which uses high amplitude resonant soundwaves. Tijani et al., [10, 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; a low temperature of  $-65\text{ }^{\circ}\text{C}$  for the COP of 1.06 was reported at the cold heat exchanger which is the lowest temperature reported till now. 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 a significant effect on the TAR performance. They have also suggested that the optimization of these parameters is 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. Bheemsha et al., [14] have designed and fabricated 10W cooling load TAR for two working fluids of helium and air for operating pressure up to 10 bar. They optimized the COP of the stack and reported a value of 2.5. Prashantha et al., [15,16] designed and optimized the loudspeaker driven 10W cooling power TAR for a temperature difference ( $\Delta T$ ) of 120 K using linear thermoacoustic theory and also explained the theoretical design procedure for optimizing the resonator. 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. They conducted experiments and recorded the  $\Delta T$  of  $19.4\text{ }^{\circ}\text{C}$  for parallel plate stack for 2W cooling load at 400 Hz frequency for an operating pressure of 10 bar where helium is used as a working fluid. They also concluded that the parallel plate stacks could 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. Elnegiry et al., [19] studied the standing wave loudspeaker driven thermoacoustic heat pump for optimization using the DeltaEC software and simulated to identify the optimized operating conditions.

The 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 minimal amount of

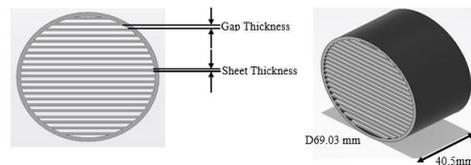
work has been carried out experimentally. However, most of these experimental works were carried out by fabricating aluminium and other metallic resonator systems resulting in conduction of heat loss. Therefore, it is crucial to conduct a detailed experimental study by constructing components of TAR using different materials with lower thermal conductivity. In this present experimental investigation, the components of TAR are fabricated by using PVC material in order to study the effect of various parameters on the TAR performance in terms of  $\Delta T$ ; hence it becomes the subject of the present investigation.

## 2. Construction and fabrication details

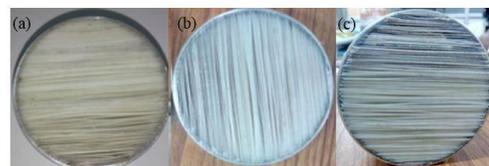
A thermoacoustic refrigerator comprises of the stack, resonator, loudspeaker and heat exchangers (hot & cold), as shown in Figure 1. A stack is the heart of TAR, which transfers heat from one end to the other by a pumping action inside the closed resonator tube, which has an inert gas environment. Copper 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 respectively. Both heat exchangers are covered with two copper mesh of 0.6 mm thickness with a 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 helium and zero air as the working fluid.



**Figure 1.** The cross-sectional view of Thermoacoustic refrigerator



**Figure 2.** Parallel plate stack schematic representation



**Figure 3.** Parallel plate stacks: (a) 0.28 mm gap, (b) 0.33 mm gap and (c) 0.38 mm gap

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. The parallel plate stack gives better performance compared to all other stack geometries [17]. In this study, aluminium sleeves and Mylar sheet material are used to fabricate the parallel plate stack to study the effect of spacing on the performance of TAR in terms of  $\Delta T$ . The schematic representation of the parallel plate stack is shown in Figure 2.

Aluminium sleeves are machined with OD 69.03 mm and ID 65.03 mm for a length of 40.5 mm. Mylar sheets are sheared to the required dimension and inserted into the slots of aluminium sleeves created by using wire EDM of 0.12 mm diameter wire. 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 Figure 3.

## 3. Details of the experimental setup

The overall experimental setup having a data acquisition system, zero air cylinder, temperature sensors and other components with connections are shown in Figure 4. The hot heat exchanger is provided with cooling water connections to remove excess heat and to maintain the hot heat exchanger temperature

closer to the atmospheric temperature of about 32 °C. An electric heater of 10W is placed on the cold heat exchanger for cooling power measurement, which is operated by a 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 the required frequency of 100–600 Hz. Cooling water circulation is provided to the acoustic driver in order to remove excess heat, which is generated due to the continuous operation of loud-speaker inside the closed resonator housing.

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 another 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. 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 are operating in the temperature range –100 °C to +100 °C are attached to the cold and hot heat exchangers.



**Figure 4.** Experimental Setup of Thermoacoustic Refrigerator

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 TAR and joints are checked for leakage and tested for pressure up to 11 bar.

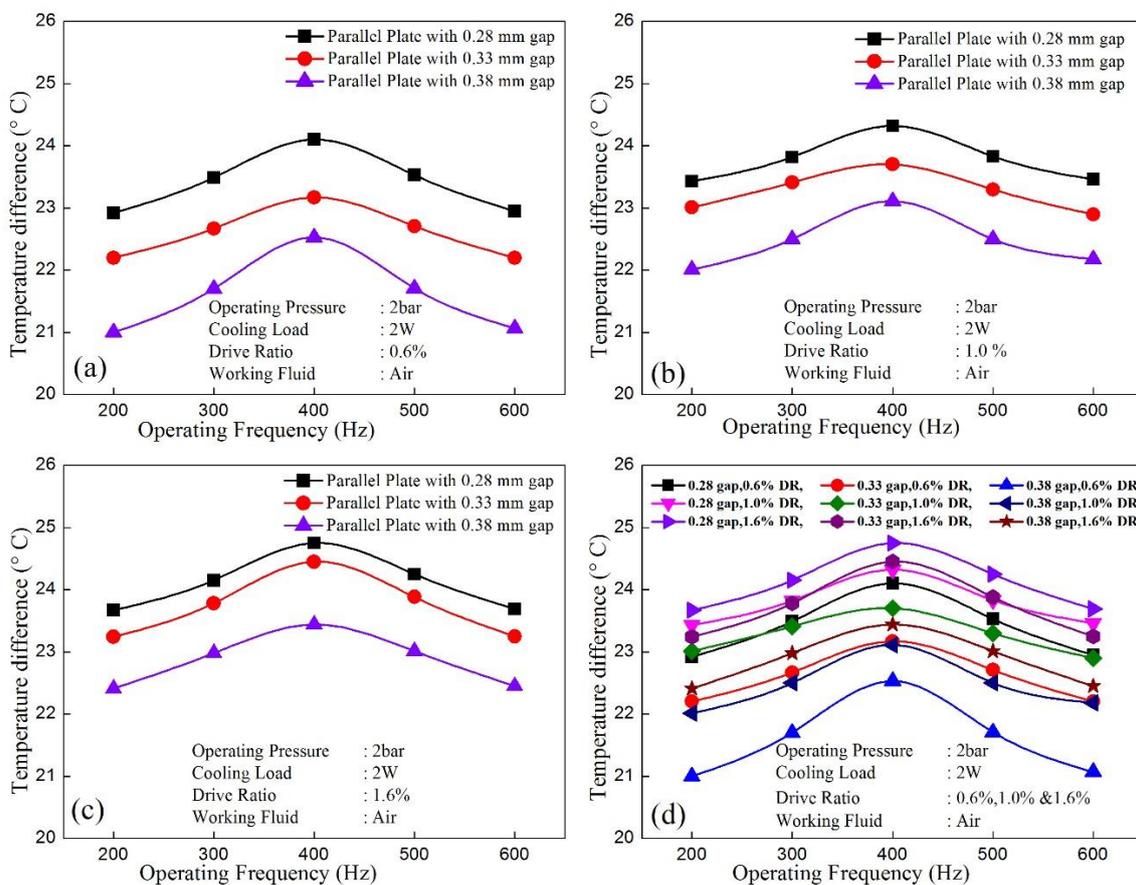
#### **4. Results and discussions**

In this experimental study, three parallel plate stacks have been considered for various drive ratios of 0.6%, 1.0%, and 1.6% with different cooling loads of 2W to 10W by using zero air as a working medium. The experimental values of  $\Delta T$  claimed in this manuscript are the average of about 36000 recorded data for each trial by developing a Visual Basic Application (VBA) program. The experimental results are presented and discussed in the subsequent sub-headings.

##### **4.1 Effect of Operating Frequency on TAR Performance for 2W Cooling Load at 2 bar Mean Operating Pressure**

The variation of  $\Delta T$  vs. operating frequency for different drive ratios have been illustrated in Figures 5 (a) – 5 (d) for a constant mean operating pressure (2 bar) and a constant cooling load (2W).

It is observed from Figure 5 (a) that the  $\Delta T$  increases with the increase in frequency up to 400 Hz and after that decreases with a further increase in frequency. It may be attributed to the fact that the influence of thermal penetration depth across the stack decreases when the operating frequency increases beyond 400 Hz leading to an increase in viscous losses, which reduces the thermoacoustic effect. This behaviour is almost similar for all other drive ratios, which can be seen in Figures 5 (b) and 5 (c). It is worthwhile to mention that for a given parallel plate stack, the  $\Delta T$  increases with the decrease in the 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 of 1.6% gives the highest  $\Delta T$  as compared to all other cases, as can be seen in Figure 5 (d). The exact numerical values of experimental results for different parallel plate stacks of 0.28 mm, 0.33 mm and 0.38 mm gap are tabulated in table 1. It is evident from table.1 that the  $\Delta T$  is maximum at about 400 Hz irrespective of the stack porosity ratios and drive ratios; this may be due to the fact that the value of  $\Delta T$  is a function of electroacoustic efficiency. The maximum electroacoustic efficiency is obtained when the mechanical resonance of the driver matches the acoustical resonance of the resonator tube.



**Figure 5.** Variation of  $\Delta T$  with operating frequency for different drive ratios (a) 0.6% (b) 1.0% (c) 1.6% and (d) combined drive ratios (0.6%, 1.0% & 1.6%)

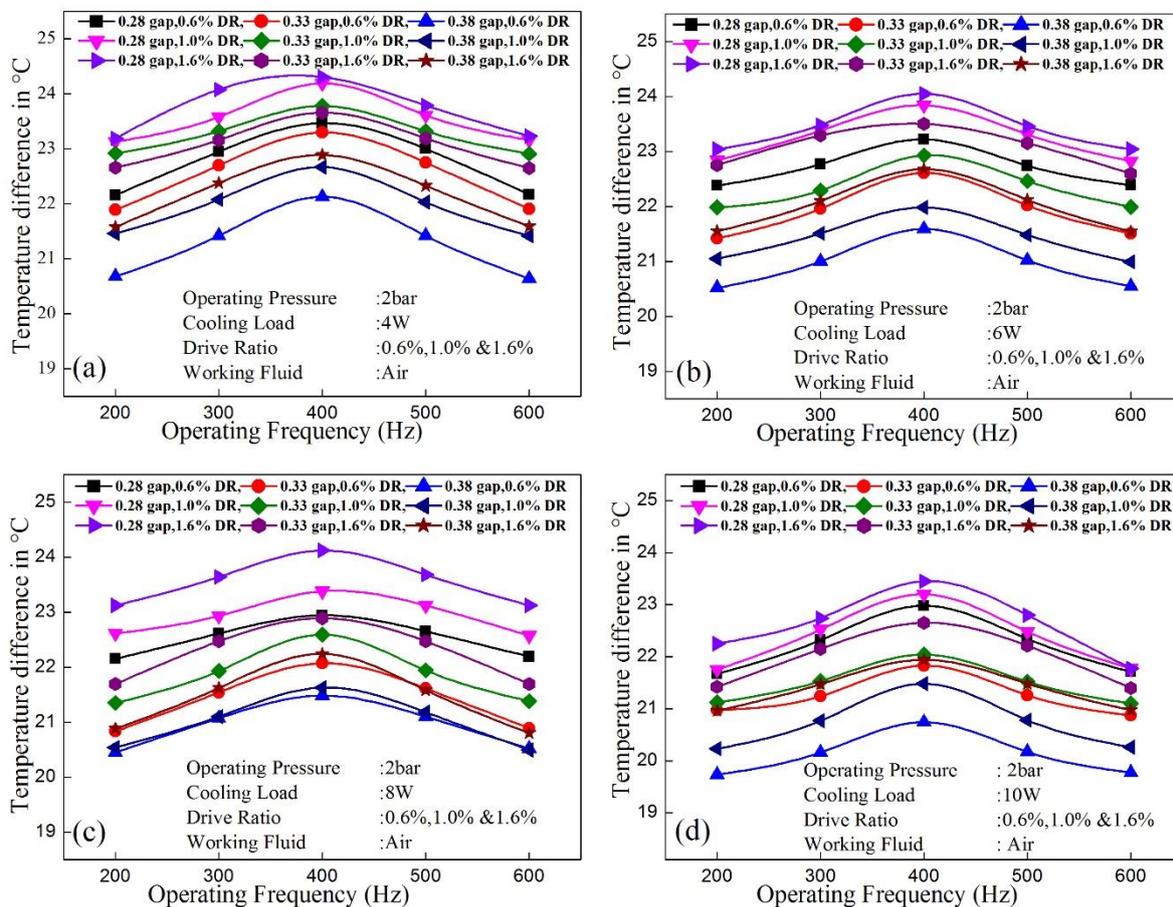
**Table 1.** Detailed experimental results with 2 bar operating pressure at 2 W cooling load for stack spacing of (a) 0.28 mm, (b) 0.33 mm and (c) 0.38 mm

Cooling load (W)	Drive ratio (%)	Frequency (Hz)	(a) 0.28 mm spaced stack			(b) 0.33 mm spaced stack			(c) 0.38 mm spaced stack		
			Th (°C)	Tc (°C)	$\Delta T$ (°C)	Th (°C)	Tc (°C)	$\Delta T$ (°C)	Th (°C)	Tc (°C)	$\Delta T$ (°C)
2	0.6	200	31.24	8.32	22.92	31.08	8.88	22.20	31.41	10.41	21.00
2	0.6	300	31.23	7.74	23.49	31.15	8.48	22.67	31.41	9.71	21.70
2	0.6	400	31.24	7.14	24.10	31.35	8.18	23.17	31.45	8.92	22.53
2	0.6	500	31.22	7.69	23.53	31.29	8.58	22.71	31.41	9.70	21.71

2	0.6	600	31.22	8.27	22.95	31.10	8.90	22.20	31.37	10.30	21.07
2	1.0	200	31.35	7.92	23.43	31.15	8.14	23.01	31.54	9.53	22.01
2	1.0	300	31.43	7.61	23.82	31.13	7.72	23.41	31.36	8.86	22.50
2	1.0	400	31.18	6.86	24.32	31.11	7.41	23.70	31.10	7.99	23.11
2	1.0	500	31.13	7.30	23.83	31.13	7.83	23.30	31.38	8.88	22.50
2	1.0	600	31.38	7.92	23.46	31.13	8.23	22.90	31.58	9.40	22.18
2	1.6	200	31.29	7.32	23.97	31.23	7.51	23.72	31.19	8.58	22.61
2	1.6	300	31.39	7.24	24.15	31.15	7.37	23.78	31.23	8.25	22.98
2	1.6	400	31.44	6.42	25.02	31.37	6.61	24.76	31.28	7.84	23.44
2	1.6	500	31.50	7.25	24.25	31.17	7.29	23.88	31.23	8.22	23.01
2	1.6	600	31.29	7.30	23.99	31.29	7.64	23.65	31.22	8.57	22.65

#### 4.2 Effect of Operating Frequency on TAR Performance for 4W to 10W Cooling Loads at 2 bar Mean Operating Pressure

The effect of porosity ratio and drive ratio on  $\Delta T$  has been studied for different cooling loads, as seen in Figures 6 (a) – 6 (d) for a constant mean operating pressure of 2 bar.



**Figure 6.** Variation of  $\Delta T$  with operating frequency for different drive ratios (0.6%, 1.0% & 1.6%) by considering different cooling loads of (a) 4W (b) 6W (c) 8W and (d) 10W

It is observed from Figure 6 (a) that the value of  $\Delta T$  increases with the increased operating frequency and found to be maximum at 400 Hz and decreases after that irrespective of drive ratio, mean operating pressure, cooling load, and spacing between the stacks. It is worthwhile to mention that the value of  $\Delta T$  is found to be significantly higher for the stack with 0.28 mm gap at 1.6% drive ratio. However, it is found to be insignificant for the stack with 0.38 mm gap at 200 Hz and 600 Hz operating frequency for a particular drive ratio of 0.6%. Similar characteristics can also be observed for higher cooling loads

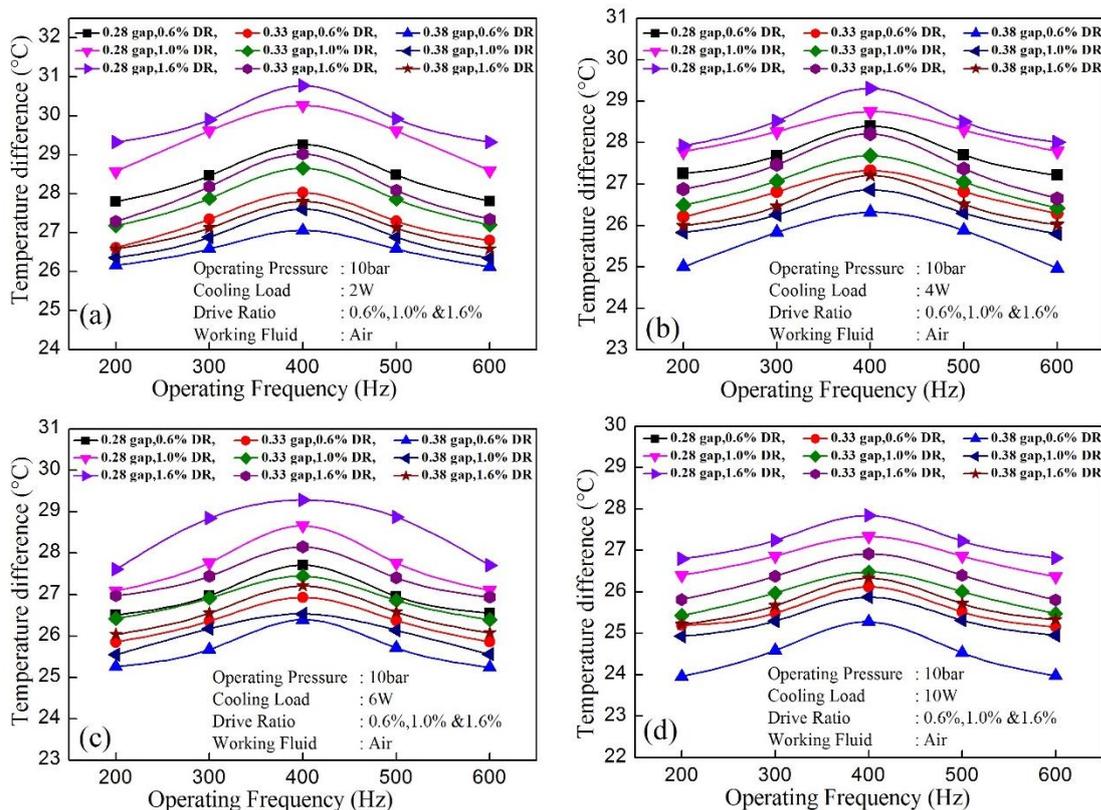
(6W, 8W and 10W) and can be observed in Figures 6 (b) – 6 (d). It can be concluded from Figures 6 (a) – 6 (d) that the magnitude of  $\Delta T$  continuously decreases with the increase in cooling load and is found to be least at 10W cooling load. The consolidated numerical values of experimental results at 400 Hz operating frequency are presented in table 2.

**Table 2.** The significant numerical values of experimental results with 2 bar operating pressure for different cooling loads at 1.6% drive ratio with stack spacing of (a) 0.28 mm, (b) 0.33 mm and (c) 0.38 mm at 400 Hz operating frequency

Cooling load (W)	Drive ratio (%)	Frequency (Hz)	(a) 0.28 mm spaced stack			(b) 0.33 mm spaced stack			(c) 0.38 mm spaced stack		
			Th (°C)	Tc (°C)	$\Delta T$ (°C)	Th (°C)	Tc (°C)	$\Delta T$ (°C)	Th (°C)	Tc (°C)	$\Delta T$ (°C)
4	1.6	400	31.57	7.26	24.31	31.36	7.54	23.82	31.28	8.89	22.39
6	1.6	400	31.57	7.52	24.05	31.35	7.85	23.50	31.52	9.85	21.67
8	1.6	400	31.68	7.48	24.20	31.13	8.02	23.11	31.71	10.47	21.24
10	1.6	400	31.50	8.05	23.45	31.55	8.90	22.65	31.56	10.62	20.94

#### 4.3 Effect of Operating Frequency on TAR Performance for 2W to 10W Cooling Loads at 10 bar Mean Operating Pressure

The influence of drive ratio and stack spacing on  $\Delta T$  has been studied for different DR cooling loads (2W – 10W), as can be seen in Figures 7 (a) – 7 (d) for a constant mean operating pressure of 10 bar.



**Figure 7.** Variation of  $\Delta T$  with operating frequency for different drive ratios (0.6%, 1.0% & 1.6%) by considering four different cooling loads of : (a) 2W (b) 4W (c) 6W and (d) 10W

It is crucial to mention that at 2W cooling DR load and 10 bar operating pressure [Figure 6 (a)], the difference in temperature is found to be significantly higher as compared to all other operating pressures (i.e., 2 bar to 8 bar). It is essential to mention that a stack of 0.28 mm gap with a drive ratio 1.6% gives the highest  $\Delta T$  at 400 Hz operating frequency as compared to all other operating conditions, as can be

seen in Figure 7 (a). The significant numerical values of experimental results at 10 bar mean operating pressure are tabulated in table 3.

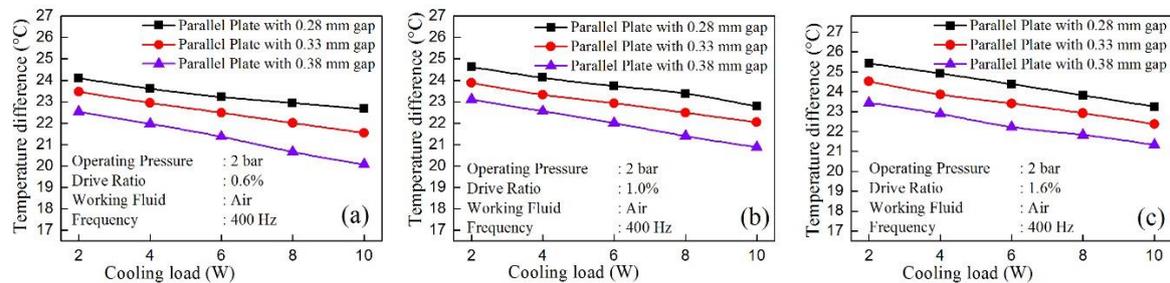
Nevertheless, the effect of 4 bar, 6 bar, and 8 bar operating pressures by considering various testing conditions have also studied. They are not shown here in order to avoid repetitions. However, the results of 4 bar to 8 bar lies in between 2 bar and 10 bar operating pressures.

**Table 3.** The significant condition's numerical values of experimental results with 10 bar operating pressure for different stack spacing of (a) 0.28 mm. (b) 0.33 mm and (c) 0.38 mm at 400 Hz operating frequency

Cooling load (W)	Drive ratio (%)	Frequency (Hz)	(a) 0.28 mm spaced stack			(b) 0.33 mm spaced stack			(c) 0.38 mm spaced stack		
			Th (°C)	Tc (°C)	$\Delta T$ (°C)	Th (°C)	Tc (°C)	$\Delta T$ (°C)	Th (°C)	Tc (°C)	$\Delta T$ (°C)
2	1.6	400	31.60	0.83	30.77	30.89	1.67	29.22	31.42	3.62	27.80
4	1.6	400	31.58	2.27	29.31	32.08	3.72	28.36	31.67	4.07	27.60
6	1.6	400	31.66	2.38	29.28	32.33	4.18	28.15	31.86	4.35	27.51
10	1.6	400	31.54	3.69	27.85	32.81	8.01	25.95	31.83	5.50	26.33

#### 4.4 Effect of Cooling Load on the Performance of TAR in terms of $\Delta T$ at 2 bar Mean Operating Pressure

The repercussion of cooling load and other operating parameters on the value of  $\Delta T$  has been studied for a pressure of 2 bar and 400 Hz operating frequency. This can be seen in Figures 8 (a) – 8 (c) for three different drive ratios. It is observed from Figure 8 (a) that the  $\Delta T$  is a function of cooling load. As the cooling load increases  $\Delta T$  decreases. For the 2W cooling load, the  $\Delta T$  is higher because the required acoustic power is adequate to take away heat developed in the stack whereas,  $\Delta T$  is lower for 10W cooling load as the required acoustic power is not sufficient to remove heat. Very similar behaviour can also be seen for higher drive ratios, as can be observed in Figure 8 (b) and Figure 8 (c).



**Figure 8.** Variation of  $\Delta T$  against cooling loads at 2 bar mean operating pressure at 400 Hz frequency with drive ratios of a) 0.6%, (b) 1.0%, and (c) 1.6%.

It is also observed from Figures 8 (a) – 8 (c) that the value of  $\Delta T$  increases with the increase in drive ratio. It is found that a stack of 0.28 mm gap with a drive ratio of 1.6% gives the highest  $\Delta T$  as compared with all other cases. The overview of numerical results at 400 Hz operating frequency for a drive ratio of 0.6%, 1.0%, and 1.6% are outlined in table 4, table 5 and table 6 respectively. The overview of numerical results at 400 Hz operating frequency for a drive ratio of 1.6% is outlined in table 4.

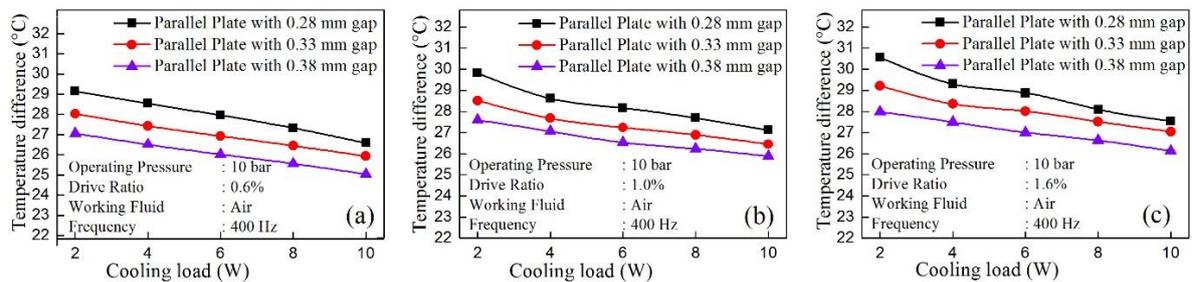
**Table 4.** The Glimpse of significant experimental results with 2 bar operating pressure for 400 Hz frequency at 1.6% drive ratio with the spacing of (a) 0.28 mm, (b) 0.33 mm and (c) 0.38 mm

Cooling load (W)	(a) 0.28 mm gap			(b) 0.33 mm gap			(c) 0.38 mm gap		
	Th (°C)	Tc (°C)	$\Delta T$ (°C)	Th (°C)	Tc (°C)	$\Delta T$ (°C)	Th (°C)	Tc (°C)	$\Delta T$ (°C)
2	31.44	6.42	25.02	31.37	6.61	24.76	31.28	31.28	23.44
4	31.57	7.26	24.31	31.36	7.54	23.82	31.28	31.28	22.39
6	31.57	7.52	24.05	31.35	7.85	23.50	31.52	31.52	21.67
8	31.68	7.48	24.20	31.13	8.02	23.11	31.71	31.71	21.24

10      31.50    8.05    23.45    31.55    8.90    22.65    31.56    31.56    20.94

#### 4.5 Effect of Cooling Load on the Performance of TAR in terms of $\Delta T$ at 10 bar Mean Operating Pressure

The effect of porosity and drive ratio on the  $\Delta T$  for any particular cooling load can be seen in Figures 9 (a) – 9 (c) at 10 bar operating pressure. The repercussion of 10 bar operating pressure on the performance of TAR in terms of  $\Delta T$  for various operating parameters is almost similar to that of 2 bar operating pressure (section 4.4). However the higher magnitude results in a  $\Delta T$  which is desirable are obtained as can be seen in Figures 9 (a) – 9 (c). The details of critical experimental results are tabulated at 400 Hz operating frequency for a drive ratio of 1.6% in table 5.



**Figure 9.** Deviation in  $\Delta T$  w.r.t. different cooling loads for a mean operating pressure of 10 bar having (a) 0.6%, (b) 1.0% and (c) 1.6% drive ratios at the constant operating frequency of 400 Hz

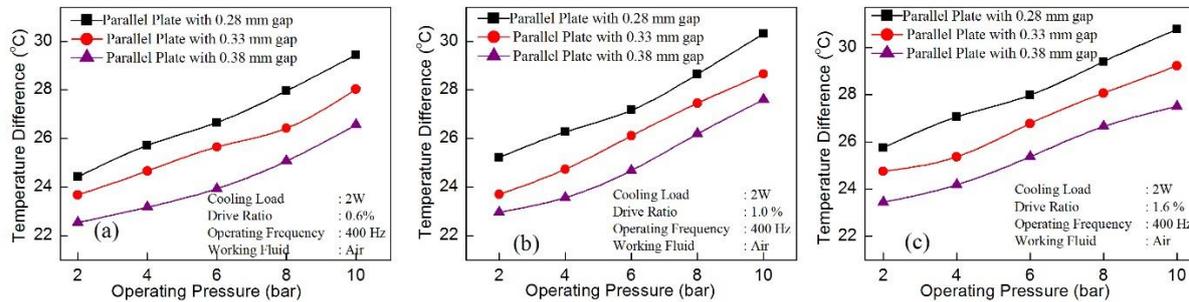
**Table 5.** Summary of critical experimental results with 10 bar operating pressure for 400 Hz frequency at 1.6% drive ratio with the spacing of (a) 0.28 mm, (b) 0.33 mm and (c) 0.38 mm

(a) 0.28 mm gap				(b) 0.33 mm gap				(c) 0.38 mm gap			
Cooling load(W)	$T_h$ (°C)	$T_c$ (°C)	$\Delta T$ (°C)	Cooling load(W)	$T_h$ (°C)	$T_c$ (°C)	$\Delta T$ (°C)	Cooling load(W)	$T_h$ (°C)	$T_c$ (°C)	$\Delta T$ (°C)
2	31.60	0.83	30.77	2	30.89	1.67	29.22	2	31.42	3.62	27.80
4	31.58	2.27	29.31	4	32.08	3.72	28.36	4	31.67	4.07	27.60
6	31.66	2.38	29.28	6	32.33	4.18	28.15	6	31.86	4.35	27.51
8	31.45	3.25	28.20	8	32.21	5.20	27.01	8	31.98	4.75	27.23
10	31.54	3.69	27.85	10	32.81	5.76	27.05	10	31.83	5.50	26.33

#### 4.6 Effect of Mean Operating Pressure on the Performance of TAR in terms of $\Delta T$ at 2 bar Mean Operating Pressure

The impact of mean operating pressure on the performance of TAR in terms of  $\Delta T$  is studied for five pressures of 2, 4, 6, 8, and 10 bars under different operating conditions.

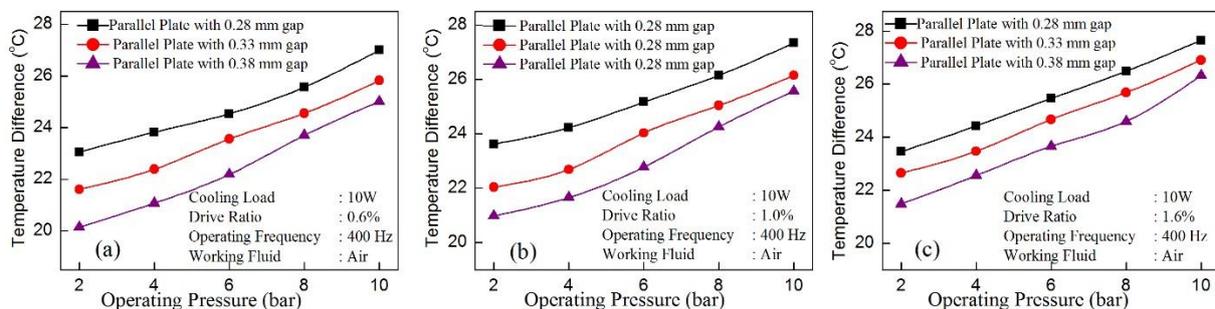
The effect of mean operating pressure on the performance of TAR for any given drive ratio, cooling load, and porosity ratio for the 2W cooling load is depicted in Figures. 10 (a) – 10 (c) at 400 Hz operating frequency. It can be observed from Figure 10 (a) that as the operating pressure increases, the  $\Delta T$  also increases irrespective of cooling load, porosity ratio, and operating frequency. Also, there is an increase in  $\Delta T$  as the drive ratio increases from 0.6% to 1.6%. It is significant to mention that the  $\Delta T$  is at its best at 10 bar mean operating pressure, hence it is essential to operate the refrigerator at higher pressures to get an enhanced performance to match with the performance of the conventional refrigerator.



**Figure 10.** Variation of  $\Delta T$  for 2W cooling load at 400 Hz operating frequency with a drive ratio of a) 0.6% b) 1.0% and c) 1.6%.

#### 4.7 Effect of Mean Operating Pressure on the Performance of TAR in terms of $\Delta T$ at 2 bar mean operating pressure

The performance of TAR for different operating pressure has been examined for any given drive ratio, cooling load, and porosity ratio. This is shown in the following Figures 11 (a) – 11 (c) at 400 Hz operating frequency and 10W cooling load. By comparing the results shown in Fig 11 (a) – 11 (c) (for 2W cooling load) with the results shown in Fig 11 (a) – 11 (c) (for 10W cooling load) we can see that the performance trend is maintained with the only difference that the magnitude of  $\Delta T$  diminishes. The experiment is also conducted with 4W, 6W and 8W cooling loads; in each case, it was found that the result was not as good as with previously used cooling loads.



**Figure 11.** Variation of  $\Delta T$  for 10W cooling load at 400 Hz frequency with a drive ratios of a) 0.6% b) 1.0% and c) 1.6%.

## 5. Conclusion

Experiments are conducted to study and investigate the influence of stack spacing on the TAR performance under different operating conditions. The performance of a TAR is assessed based on the different parameters such as cooling load, operating frequency, mean operating pressure, and drive ratio, and the conclusions are as follows:

- The experimental results indicate that the  $\Delta T$  between cold and hot ends of the stack is higher at 2W cooling load and lesser at 10W cooling load at any operating frequency.
- The results indicate that the stack with 0.28 mm gap performs better than that of 0.33 and 0.38 mm gaps.
- The parallel plate stack with 0.28, 0.33, and 0.38 mm gap shows a maximum  $\Delta T$  of 30.77 °C, 29.22 °C, and 27.80 °C, respectively. This result is for a particular mean operating pressure of 10 bar, cooling load of 2W with a drive ratio of 1.6% at an operating frequency of 400 Hz.

- The  $\Delta T$  of the parallel plate stack with 0.28 mm space is better compared to the other two stack geometries (0.33 mm and 0.38 mm spaced parallel plate stacks).

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