

Effect of Spacing in a Parallel Plate Stack on the Performance of Thermoacoustic Refrigerator made up of PVC for an Operating Pressure of 8 bar using Air as a Working Medium

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Abstract: In this experimental study, Poly-Vinyl-Chloride (PVC) has been used to fabricate all the structural parts of the Thermoacoustic Refrigerator (TAR) including the resonator system to minimize the conduction heat losses between the refrigerator and the surroundings. In this work, three parallel plate stacks are used to study the performance of TAR by 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 constructed by using aluminum and mylar sheets and Air is used as the working. Present research deals with the study of performance of thermoacoustic refrigerator of 10W cooling power for different operating conditions with a constant mean operating pressure of 8 bar. The experiments are conducted for three drive ratios of 0.6%, 1% and 1.6% with an operating frequencies of 200 – 600 Hz and cooling load of 2W – 10W. The effect of different parameters on the performance of thermoacoustic refrigerator such as operating frequency, cooling load and drive ratios are studied. Experimental results shows that the lowest temperature measured at cold heat exchanger is 1.91 °C while the hot heat exchanger temperature is maintained between 31 °C – 32 °C. The highest value of temperature difference (ΔT) measured is 29.44 °C which shows the improvement of about 32% increase in the temperature difference than the previous findings where aluminum resonator is used. The highest Coefficient of Performance (COP) and the Relative Coefficient of Performance (COPR) are found to be 1.490 and 0.137 respectively.

Keywords - Thermoacoustic Refrigerator; Drive Ratio; Parallel Plate Stack; COP; COPR; Temperature Difference.

I. INTRODUCTION

In the current century, environmental issues have become a key concern in the design, development and manufacturing of heat pumps, refrigerators and air conditioning system. As the existing refrigerators produces hazardous refrigerants which develops CFCs (Chlorofluorocarbons) and HCFCs (Hydro-chlorofluorocarbons) by which the ozone layer is getting damaged. By considering these environmental pollution and their effects it is necessary to develop a viable alternate refrigerating system which is free from usage of chemicals and refrigerants. Thermoacoustic refrigeration is a new alternate cooling technology to existing conventional cooling technology with merits of environmental safety, simplicity, higher reliability, lower manufacturing cost (if produced in mass production), free from usage of chemicals and refrigerants. A thermoacoustic engine is a novel prime mover with no moving parts whose potential of long life attracts industries, researchers and academic interests. The quick advances in the theory of thermoacoustics, modelling and development are most promising, and the expectation is that thermoacoustics will become commercially viable in the near future. In this connection several researchers have oriented towards the development of thermoacoustic refrigeration system where, sound waves are used to produce pressure waves which compress and expands the gas particles inside the closed resonator tube. Air or non-flammable inert gases like helium, argon, neon, xenon, etc. are used as a working fluid for the operation of thermoacoustic devices to produce required cooling effect. Heat exchangers, stack, resonator and driver are used to construct a basic thermoacoustic refrigerator. A loud speaker or driver is used depending upon the type of engine to produce acoustic sound waves, these sound waves when operated in closed resonator tube with working gas create resonance at certain frequencies called resonance frequencies which are determined by the resonator length. At a particular location in the resonator if the stack is placed by having standing wave in the resonator, the ΔT can be measured across the stack by placing heat exchanger at both sides of the stack.

Thermoacoustic phenomena was first observed and studied for more than two hundred years ago however, the greater depth of understanding of the phenomena has been developed over the past four decades. In the year 1777, Byron Higgins [1] made the first observation and investigation of organ pipe type oscillations by appropriately positioning a hydrogen flame inside a tube which is open at both sides at certain position, acoustic oscillations were observed known as Singing Flames. In 1850, a tube with closed end on one side also generate sound from heat if the closed end is very hot, such a device is called a Soundhauss tube. Soundhauss [2] became the first person to do quantitative research on thermoacoustics where he performed experiments in a hollow glass tube with one end open and other end closed. In the year 1859, Rijke [3] explained that when the heated wire screen is placed at lower half of the open ended pipe, the strong oscillations were produced.

In 1969, Rott [4] continued the work of Kramers [5] in a series of technical papers, where a successful linear theory of thermoacoustics was given. More advances in the understanding of the thermoacoustic phenomena was explained by Rott. In 1975, H. Thomann and Hofler [6] helped to initiate attempts for the development of thermoacoustic devices intended for practical cooling applications. In the year 2002, Tijani et al., [7, 8] had reported a quantitative experimental investigation into the effect of the pore dimensions on the performance of thermoacoustic devices. Parallel plate stacks with spacing varying between 0.15 mm and 0.7 mm had been constructed. They have showed that the stack with 0.25 mm spacing is optimum for the performance defined by the relative coefficient of performance (COPR). They also developed a design methodology for a loud speaker driven TAR and the targeted temperature of their refrigerator was -65°C , which can be achieved with a drive ratio of 3%. Linear thermoacoustic theory is the basis for the design methodology of their thermoacoustic refrigerator. In the year 2011, Bheemsha et al., [9] designed and fabricated the thermoacoustic refrigerator for 10W cooling power for both helium and air as the working medium. By maintaining the optimized value of diameter ratio ($D2/D1$) of 0.43 the acoustic losses in the small diameter resonator tube were minimized. They have also designed buffer volume and resonator for optimization which was verified by using MAT Lab and found that maximum cooling effect was found at the position of maximum pressure amplitude (pressure antinode). In the year 2012, Bheemsha et al., [10] conducted experiments for four different stacks by using a 10W cooling power thermoacoustic refrigerator made up of aluminum and the maximum temperature difference reported was 18°C for parallel plate stack with helium as a working medium for a drive ratio of 1.6% at 10 bar operating pressure. In 2014, Tartibu et al., [11] developed a novel mathematical programming model to optimize the performance of a simple thermoacoustic refrigerator, which provides fast engineering estimates to initial design calculations. In their study, they optimized the blockage ratio, stack length, stack position and the plate spacing. In the year 2016, Zolpakar et al., [12] conducted experimental work based on the results of Multiobjective Genetic Algorithm (MOGA) optimization scheme for a standing wave thermoacoustic refrigerator. The effect of the stack center position (x_{sn}), stack length (L_{sn}) and the blockage ratio (B) on the cooling power, acoustic power and COP are examined experimentally by using spiral and celcor stack plate.

In the year 2017, Ramesh Nayak B et al., [13] studied the influence of stack geometry on the performance of thermoacoustic refrigerator under various operating conditions for four different types of stacks i.e. parallel plate stack of 0.33 mm gap made of mylar sheet of 0.12 mm thick and 3 circular stacks of 1 mm, 2 mm and 3 mm diameter. They conducted experiments and recorded the temperature difference of 19.4°C for parallel plate stack with 2W cooling load at 400 Hz operating frequency for an operating pressure of 10 bar with helium as a working fluid. They also concluded that the parallel plate stacks were able to create more temperature difference compared with circular stacks. In 2018, B G Prashantha et al., [14] designed and analysed the acoustically driven refrigerator for 50W cooling power at operating pressure of 10 bar with 3% drive ratio for a temperature difference of 75K. The stack and heat exchangers were designed by considering 75% porosity ratio, the position of the stack and the corresponding dimensions were discussed. The same model was simulated in DeltaEC software which predicts the cold heat exchanger temperature of -3.4°C at 0.882 COP and -4.3°C at 0.841 COP for 1/3rd wave length and 1/4th wave length resonator design respectively.

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 aluminum and other metallic resonator systems resulting in the conduction heat loss. Therefore, it was felt that it is crucial to conduct a detailed experimental study by constructing components of TAR using different materials with lower thermal conductivity. In the present experimental investigation, the components of TAR are fabricated by using PVC materials in order to study the effect of various operating parameters.

II. CONSTRUCTION, FABRICATION AND EXPERIMENTAL SET UP DETAILS

A thermoacoustic refrigerator comprises of a stack, resonator, loud speaker or driver and heat exchangers (hot & cold) as shown in Fig.1. The stack is heart of the TAR, which transfers heat from one side to another by pumping action through inert gas environment inside the closed resonator tube. Also, both sides of the stack are fastened by heat exchangers. Both the heat exchangers are covered with two copper mesh of 0.6 mm thickness with porosity ratio of about 75%, which helps to enhance the rate of heat transfer as shown in Fig.3. All the structural components of TAR including resonator are constructed using PVC due to its insulating character and ease of manufacturing. 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 32°C . An electric heater of about 10W is placed on the cold heat exchanger for cooling power measurement, which is operated by 5A/30V DC power supply unit. 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 to the driver end to measure the dynamic pressure produced by the acoustic driver.

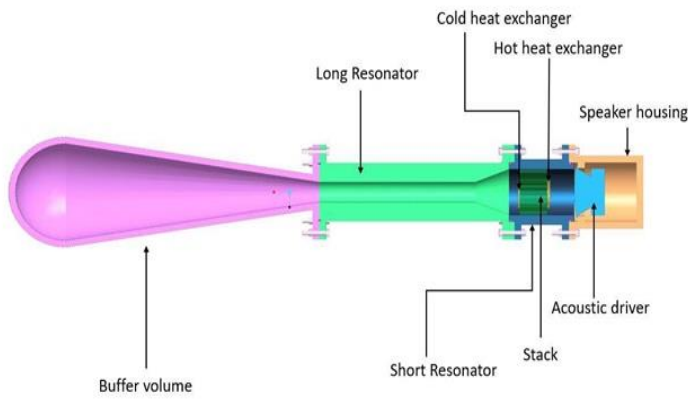


Fig. 1: Cross-sectional view of Thermoacoustic Refrigerator



Fig. 2 : Experimental setup of Thermoacoustic Refrigerator

A Bourdon tube pressure gauge in the range of 0 – 30 bar is installed in the buffer volume section to measure and verify the actual pressure of working fluid available inside the refrigerator. The temperature and pressure sensors are checked and verified for the functionality and calibrated by the certified suppliers for proper functioning. The complete setup of thermoacoustic refrigerator and joints are checked for leak proof and tested for pressure upto 10 bar. The overall experimental setup having Bruel & Kjaer data acquisition system, air cylinder, DC power supply unit and other necessary connections are shown in Fig.2.

The TAR is designed and constructed for a cooling load of 10W using pure helium and air as the working fluid by using PVC for all the structural parts.

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 [13]. 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. Aluminium sleeves are machined with OD 69.03 mm, 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. 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.4.



Fig 3: Modified heat exchangers with copper mesh attached to both hot and cold heat exchangers



Fig 4: Parallel plate stacks prepared for testing with different porosity ratios

III. EXPERIMENTAL PROCEDURE

To study the influence of spacing between the two successive plates of a stack on the TAR performance the experiments are conducted by considering various operating conditions for three different parallel plate stack geometries. The TAR resonating system is filled with air of constant mean operating pressure of 8 bar. The required operating frequency was tuned and then slowly increased from 200 Hz to 600 Hz depending upon the test requirement for each test reading. The cooling load is supplied by using resistance heating coil which is attached to cold heat exchanger controlled by 5A/30V DC power supply unit. The testing data is recorded after the system got stabilized for each trial by maintaining constant operating pressure. The experiments are conducted by varying cooling load, drive ratio and operating frequency for each trial. The detailed flow chart for testing is shown in Fig. 5.

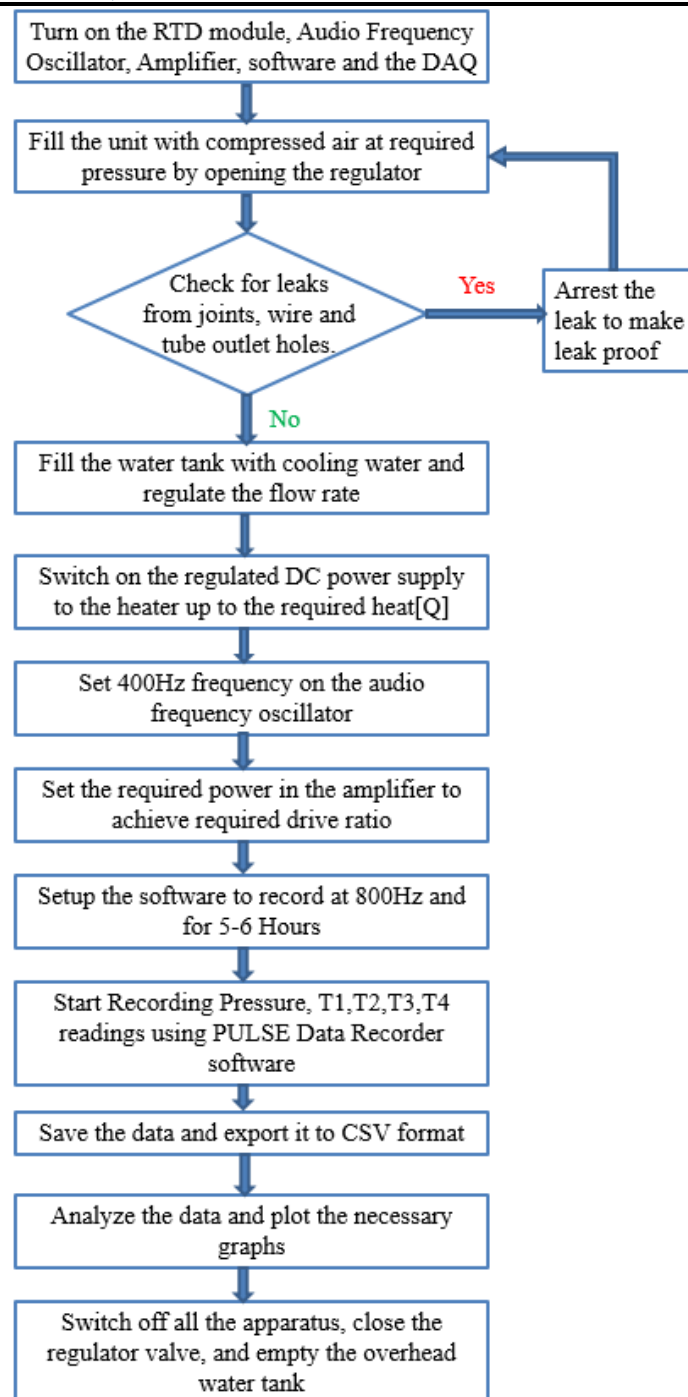


Fig.5 : Procedure for Experimentation

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The Experiments are conducted with three parallel plate stacks for different cooling loads of 2W to 10W, different drive ratios of 0.6%, 1.0% and 1.6% with air as working medium, the results are further discussed.

4.1 Effect of Operating Frequency on the Performance of Thermoacoustic Refrigerator for 2W Cooling Load at 8 bar Mean Operating Pressure

The variation of temperature difference (ΔT) over the frequency range for different drive ratios with 2W cooling load has been illustrated in Fig. 6 (a) – Fig. 6 (c) at a constant mean operating pressure of 8 bar.

From Fig.6 (a) it can be observed that temperature difference (ΔT) increases linearly as the operating frequency increases up to 400 Hz and thereafter reduces with further increase in operating frequency. This behavior is due to the influence of thermal penetration depth across the stack decreases as the operating frequency increased beyond 400 Hz. This behavior is almost similar for drive ratios of 1.0% and 1.6%, which can be seen in Figs 6 (b) and 6 (c). It is also observed from Figs 6 (a – c) that the ΔT increases with increase in drive ratios. It is worthwhile to mention that for a given parallel plate stack, the value of ΔT increases with the decrease in the gap between two successive plates irrespective of drive ratios.

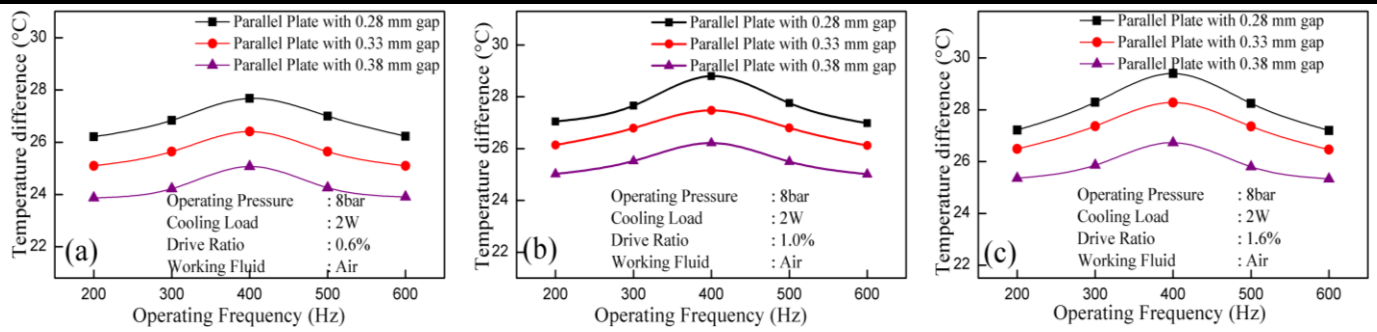


Fig.6: Variation of temperature difference (ΔT) with operating frequency for 2W cooling load at 8 bar mean operating pressure for a drive ratio of : (a) 0.6% (b) 1.0% and (c) 1.6%

It is found that a stack of 0.28 mm gap with a drive ratio of 1.6% gives the highest ΔT as compared with 0.33 mm and 0.38 mm spaced stack. From Fig. 6 (a) – Fig. 6 (c) it is evident that the refrigerator performs better in terms of temperature difference when it is operated at higher drive ratio of 1.6% as compared with lower drive ratios keeping all other variables constant.

4.2 Effect of Operating Frequency on the Performance of Thermoacoustic Refrigerator for 4W – 10W at 8 bar Mean Operating Pressure

The effect of drive ratio and porosity ratio in terms of spacing on ΔT for different cooling loads are depicted in Figs 7 (a) – 7 (d) at a constant pressure of 8 bar for different cooling loads.

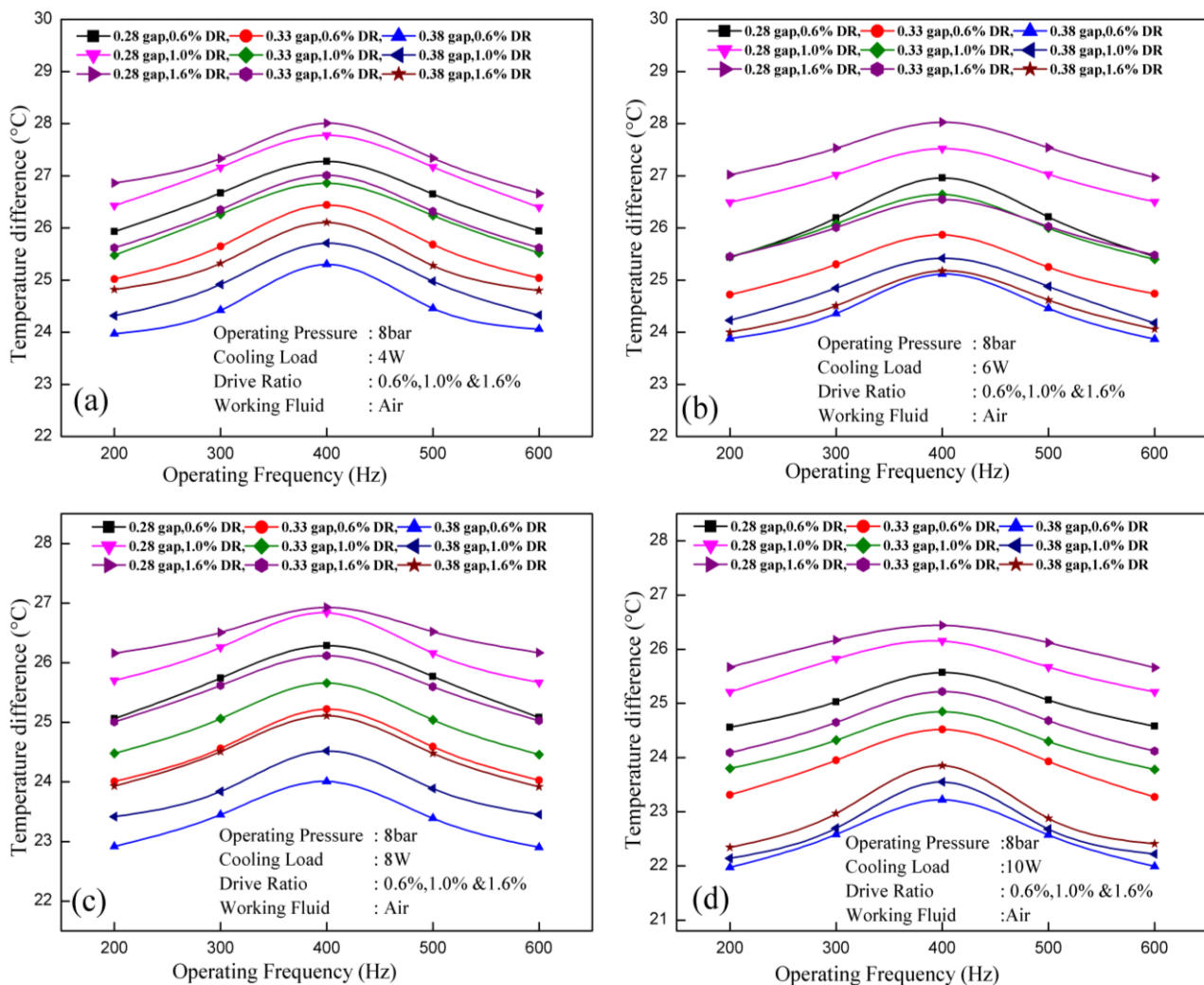


Fig. 7: Variation of ΔT vs. operating frequency for three parallel plate stack geometries and different drive ratios (0.6%, 1.0% & 1.6%) by considering four different cooling loads: (a) 4W (b) 6W (c) 8W (d) 10W

From Fig. 7 (a) it can be observed that the value of ΔT increases with the increase in operating frequency and found to be highest at 400 Hz and decreases thereafter irrespective of the cooling load, drive ratio and porosity ratio of the stacks. For the stack with 0.28 mm gap at 1.6% drive ratio for 400 Hz operating frequency the value of ΔT was found to be significantly higher, however, it is found to be insignificant for the stack with 0.38 mm gap for 200 Hz and 600 Hz operating frequency at a particular drive ratio of 0.6%. The similar characteristics are observed for higher cooling loads (6W, 8W and 10W) except that the magnitude of ΔT decreases as the cooling load increases and can be observed in Figs 7 (b) – 7 (d).

4.3 Performance of TAR in terms of COP for 8 bar mean operating pressure

The effect of cooling load and drive ratios on the performance of TAR in terms of COP at 8 bar constant operating pressure for three different stacks are exemplified in Figs 8 (a) – 8 (c). It is observed from Figs 8 (a) – 8 (c) that the cooling load has direct effect on COP, i.e. as the cooling load increases the COP also increases linearly. It is important to note that the COP decreases slightly as the drive ratio increases. It is worth to mention that the stack with 0.28 mm gap achieves highest COP at 0.6% drive ratio as compared to other two stacks.

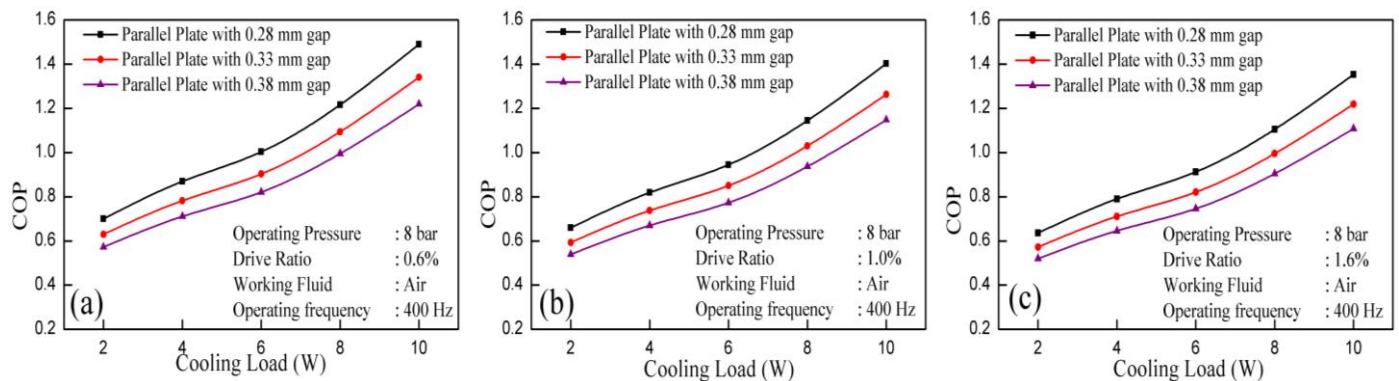


Fig.8: Variation of COP with cooling loads at 8 bar mean operating pressure for drive ratios: (a) 0.6% (b) 1.0% (c) 1.6% at 400 Hz operating frequency

4.4 Performance of TAR in terms of COPR for 8 bar operating pressure

The effect of cooling load, stack spacing and drive ratios on the performance of TAR in terms of COPR for different stacks at constant pressure (8 bar) is illustrated in Figs 9 (a – c). COPR is a function of cooling load and drive ratio, i.e. COPR increases as the cooling load increases and reduces with increase in drive ratio which is shown in Fig.9 (a) – 9 (c). It is worth to notice that the stack with 0.28 mm spacing performs better than other two stacks irrespective of drive ratio, cooling load and operating frequency. COPR of 0.137 was found to be highest for 10W cooling load at 8 bar operating pressure for an operating frequency of 400 Hz at 0.6% drive ratio.

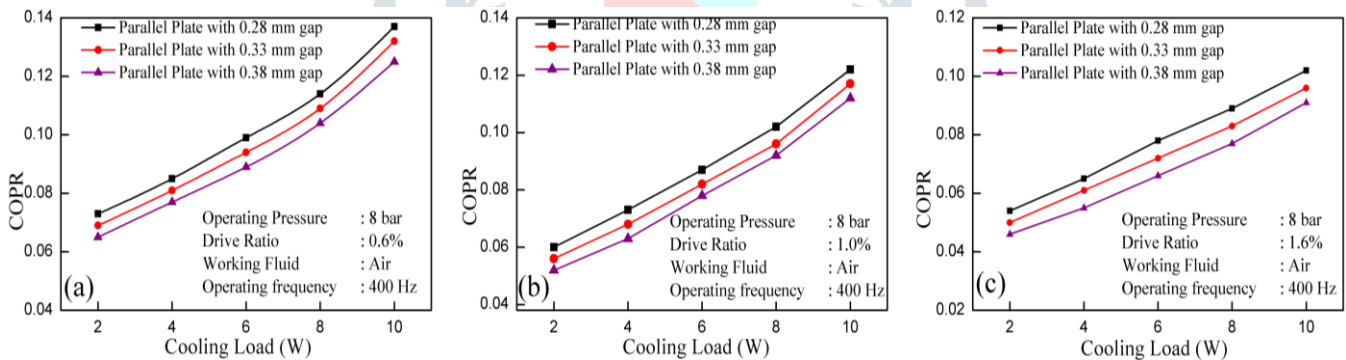


Fig. 9: Variation of COPR with cooling loads for drive ratios of: (a) 0.6% (b) 1.0% (c) 1.6% at constant pressure and constant frequency of 8 bar and 400 Hz respectively

4.5 Effect of cooling loads on TAR performance in terms of ΔT at 8 bar pressure

The effect of cooling load, drive ratio and stack spacing on the performance of TAR in terms of ΔT for three different stacks at 400 Hz operating frequency is as shown Figs 10 (a) – 10 (c). It is observed from Fig.10 (a) that the ΔT is a function of cooling load, as the cooling load increases the ΔT decreases, i.e., temperature difference of higher value is achieved for lower value of cooling load. For 2W cooling load, the temperature difference is higher since, adequate acoustic power is available to take away heat developed in the stack whereas, the ΔT is lower for 10W cooling load as the acoustic power required is not sufficient to remove heat. The similar behavior can also be seen for higher drive ratios, which can be observed in Fig.10 (b) and Fig.10 (c). It is also observed from Figs 10 (a – c) that the value of ΔT increases with the increase in drive ratio. It is very important to mention that for a given parallel plate stack the temperature difference increases with decrease in gap between two successive plates keeping the thickness constant. It is found that for a stack of 0.28 mm gap with a drive ratio of 1.6% gives highest temperature difference as compared with all other cases.

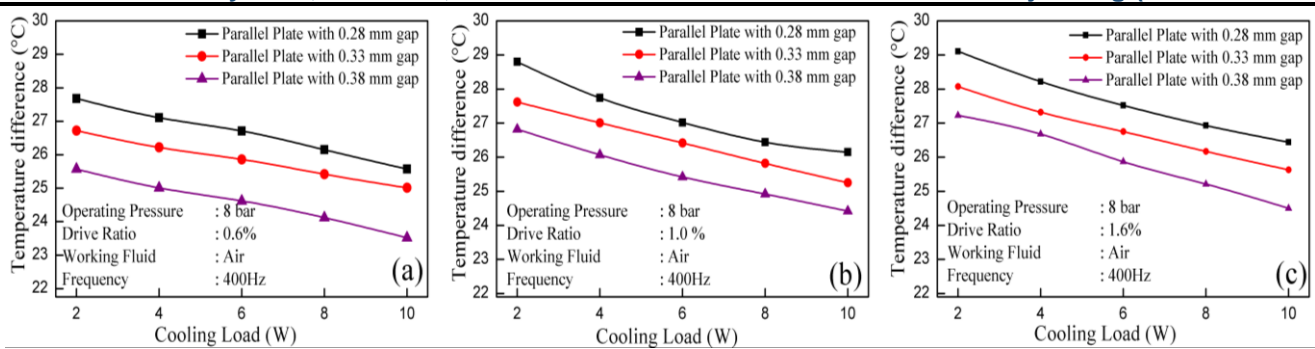


Fig.10: Variation of ΔT against cooling loads for three parallel plate stack geometries at 400 Hz operating frequency with drive ratios of: a) 0.6%, (b) 1.0% and (c) 1.6%

V. CONCLUSION

To investigate the influence of spacing on the thermoacoustic refrigerator performance under varying operating conditions an experimental study has been conducted at a constant mean operating pressure of 8 bar. The parallel plate stack and the effect of gap between the two adjacent plates on the thermoacoustic refrigerator performance is studied experimentally and the critical evaluation of the results obtained and their significance on the performance is reported. The difference in temperature between the two sides (hot and cold) of the stack is more for lesser value of cooling load, i.e. at 2W, ΔT is maximum and it decreases as the cooling load is increased from 2W to 10W for any operating frequency. The maximum temperature difference achieved is 29.4 °C for 0.28 mm, 28.28 °C for 0.33 mm and 26.73 °C for 0.38 mm spaced parallel plate stack for cooling load of 2W with drive ratio 1.6% at an operating frequency of 400 Hz. Best values of COPs obtained for the experimental study of 0.28 mm, 0.33 mm and 0.38 mm spaced parallel plate stacks for operating frequency of 400 Hz at 0.6% drive ratio while the cooling load is set for 10W is 1.49, 1.341 and 1.219. The experimental results indicate that the stack with 0.28 mm gap performs better than that of the other two stacks.

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