Comparison of Experimental and DELTA-EC Results on performance of Thermoacoustic Refrigerator

Ramesh Nayak B[1], Pundarika G[2]

[1]*Department of Industrial Engineering and Management,B. M. S. Engineering College, Bengaluru – 560019, India,*
[2]*Government Engineering College, Ramanagaram – 562159, Karnataka, India.*

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Abstract: *The performances of thermoacoustic refrigerator under different operating conditions were studied experimentally and theoretically using DELTA-EC model. The experiments were conducted for 0.12 mm thick parallel plate stack spaced at 0.36 mm of Mylar material and working fluid used was Helium. The resonator tube was made-up of aluminium and inner portion coated with 2 mm thick of polyurethane to reduce the heat losses from conduction. The experiments were conducted with heating load (HL) ranging from 2 watts to 10 watts in steps of 2 watts with three drive ratios (DR) of 1.6 %, 1.8% and 2.0 %. Operating frequencies varies from 200 Hz to 600 Hz in steps of 100 Hz for a pressure of 10 bar. The temperatures were recorded using thermocouples at hot end heat exchanger and cold end heat exchanger for different operating conditions. The experimental results were compared with the theoretical results using DELTA-EC model and performance of the thermoacoustic refrigerator was evaluated. It was observed that experimental and DELTA-EC results were in correlation for all the parameters considered. However, deviation in the experimental results from the DELTA-EC results at about 26% due to the viscous effects, discontinuities and turbulence present in the flow of the working gas and heat losses from the resonator tube.*

Keywords: Resonator tube, Acoustic driver, Stack, Heat exchangers, Helium gas

1. INTRODUCTION

Thermoacoustic refrigeration systems are used in various applications such as space cooling, commercial applications like beer-cooler and cryocooler. The importance of thermoacoustic refrigeration is emerging technology because of its eco-friendly operations. The various capacity of thermo-acoustic refrigeration systems and prime movers designed and developed by Swift [1]. Rott [2] developed theoretical and mathematical based heat pumps and thermoacoustic refrigeration systems. Worlikar et al. [3-5] studied numerical simulation of the thermoacousti refrigerator for flow of the working substance and heat transfer in the stack. Tijani et al. [6-7] constructed a 4W cooling power thermoacoustic refrigerator to study the influence of spacing between the stack plate geometry and Prandtl number of the working medium. They achieved –65^{o}C minimum temperature. Qiu et al. [8] investigated thermoacoustic refrigeration system under various parameters to characterize the thermoacoustic refrigerator performance and validated the experimental data. Electromechano-acoustic network model was established to find the electro-acoustic efficiency for various frequencies. Penelet et al. [9] studied the sound generation in thermoacoustic engines and experimental results were compared with the analytical results. The amplification of the sound causes the temperature difference in the thermoacoustic systems. Nsofor et al. [10] found the temperature difference of 15^{o}C across the cold and hot ends of the heat exchangers for a parallel plate stack with the influence of critical parameters on the performance of thermoacoustic refrigeration system. Bheemsha et al. [11] developed 10 watts cooling load thermo-acoustic refrigeration system using Helium gas as the working fluid and optimized the stack COP as 2.5. Tasnim et al. [12] evaluated the cooling power, the entropy generation and COP due to variation of process parameters in thermo-acoustic refrigerator. Kamble et al. [13] studied the experimental and theoretical performance of thermoacoustic prime mover using different working substances and mixtures of the working substances. The performance of the thermoacoustic prime mover was found better at 60 % of Helium and 40% of Argon gases compared to other working gas mixtures. Dion and Bakhtier [14] evaluated numerically and experimentally the effect of the inertance diameter and various lengths of the tube. Performance of a pulse tube refrigerator was predicted using the computational fluid dynamic model. The computational model predicted the difference in phase angle between the velocity and pressure. The difference is least at the centre of the tube and the amplitude of pressure is more at the optimal inertance. Experimentally investigated to study the effect of inertance for various lengths and diameters of the tube. It was found that the experimental and numerical simulation results were similar trends for the all the parameters.

Nayak et al. [15-16] studied the performance of the thermoacoustic refrigerator for various operating parameters of heating load, frequency, drive ratios and pressures for different gases and stack geometries. The highest temperature difference is obtained for 2 watts heating load with operating frequency of 400Hz at 10 bar pressure across the cold and hot sides of the stack.

Nekrasova et al. [17] studied pulse tube micro cryocooler using linear thermoacoustic theory. The system was designed using numerical simulation and optimum parameters were obtained using this model. Relative Carnot efficiency of 21% was obtained by considering the operating parameters of 25 bar mean pressure, operating frequency of 70 Hz, cooling power of 8 watts, and cold end temperature of 77 K using helium as a working gas. Saechan and Artur [18] was designed and developed the standing wave thermoacoustic engine driven travelling wave thermoacoustic cooler. The thermoacoustic system was tested for different input power. −19.7°C temperature was achieved from the cold side of the heat exchanger in the travelling wave thermoacoustic cooler for 2500 W heat supplied to the engine and relative coefficient of performance achieved was 5.94%. Fatimah et al. [19] demonstrated the vortex phenomenon across the two stack plates of 70 mm and 200 mm long and considered two operating frequencies of 13.1 Hz and 23.1 Hz. Reynolds number on the influence of turbulence on the velocity profiles inside the channel of the stack plate of 70 mm was 100 and for 200 mm stack was 125. Saechan and Isares [20] designed the travelling wave engine working at a frequency of 65 Hz using air as working substance at atmospheric pressure. They investigated the influence of various positions and lengths of the stub. The simulation and experimental result show the stub was used to maintain the acoustic wave propagated in the system. The maximum acoustic power was achieved at the optimal length and proper position of the stub. Chaiwongsa and Wongwises [21] studied the performance of an air based standing wave thermoacoustic refrigerator. They tested and compared the different blockage ratio of circular stack and spiral stack. Heat pipe having an input power of 30 W was mounted on the cold and hot heat exchangers. Heat was transferred to the heat absorber by connecting the hot end of the thermoelectric module and heat was transferred to the cold heat exchanger through the heat pipes. Tests were conducted for an operating frequency ranges from 120 Hz to 190 Hz with an electric power of 20 W for both with and without cooling load. From the results it was observed that COP of the circular stack has more compared to the COP of the spiral stack.

2. EXPERIMENTAL PROCEDURE

Thermoacoustic refrigerator was designed and fabricated for 10 watts cooling power. The important components of the thermoacoustic refrigerator are acoustic driver, resonator tube, stack, and heat exchangers. These components were designed based on thermoacoustic equations [2].

Figure 1 represents schematic diagram of the quarter wavelength thermo-acoustic refrigerator consisting of a large and small resonator tubes, acoustic driver, stack and heat exchangers. The detailed specifications of the thermoacoustic refrigerator is shown in Table-1 with parallel plate stack having 69 mm diameter and 40.5 mm length made of Mylar sheets of thickness 0.12 mm at a distance of 0.36 mm between two parallel plates.

Cold heat exchanger and hot heat exchanger were made up of copper tube and are fixed at both ends of the parallel plate stack. Heat is supplied to the cold heat exchanger and water is passed through the hot exchanger tube to maintain the atmospheric temperature. Resistance Temperature Detectors (RTD) were used to measure the temperature difference at hot end and cold end of the heat exchangers. Pressure transducers were used to measure the pressure in the resonator tube. Frequency of sound waves ranges from 100 Hz to 600 Hz with power supplied varies from 0 watts to120 watts to the acoustic driver. The frequency, pressure, and sound energy were measured using the Bruel and Kjear measuring devices.

The tests were conducted to find the performance characteristics of the thermoacoustic refrigerator for different operating parameters. The working substance Helium was filled in the refrigerator with an operating pressure was maintained at 10 bar for varying drive ratios of 1.6%, 1.8% and 2% at different frequencies ranges from 200 Hz to 600 Hz. The properties of the Helium gas as shown in Table-2. The heating load which varies from 2 watts to 10 watts in steps of 2 watts was supplied to the cold heat exchanger. Once the system reaches the steady state, the tests were conducted for varying heating load and frequency. The data was recorded for each test and repeated the tests to set the required drive ratio for varying power supplied to the acoustic driver. Cooling arrangement was made to eliminate the heat from the hot heat exchanger and acoustic driver.

Nomenclature

COP	Coefficient of Performance
COPR	Relative Coefficient of Performance
DELTA-EC	Design Environment for Low-Amplitude Thermoacoustic Energy Conversion
DR	Drive Ratio
ΔT	Temperature Difference
HL	Heating Load

Table-1: Specifications of the Thermoacoustic Refrigerator

Diameter of the large resonator tube	D_1 = 70.07 mm
Length of the large resonator tube	L_1 = 85.5 mm
Diameter of the small resonator tube	D_2 = 30.92
Length of the small resonator tube	L_2 = 238.91
Diameter of the stack	D = 69 mm
Length of the stack	L = 40.55 mm
Material of the stack	Mylar sheets
Diameter of the hot heat exchanger	d_1 = 3.86 mm
Length of the hot heat exchanger	l_1 = 249.3 mm
Diameter of the cold heat exchanger	d_2 = 1.93 mm
Length of the cold heat exchanger	l_2 = 498.6 mm
Material of the heat exchanger	Copper

Table-2: Properties of Helium gas

Sound velocity	a =1019.105 m/sec.
Prandtl number	σ = 0.6835
Ratio of specific heats	γ = 1.67
Drive ratio	D = 2% = 0.02
Viscous Penetration depth	δ_V = 0.0987 mm
Thermal Penetration depth	δ_K = 0.1194 mm

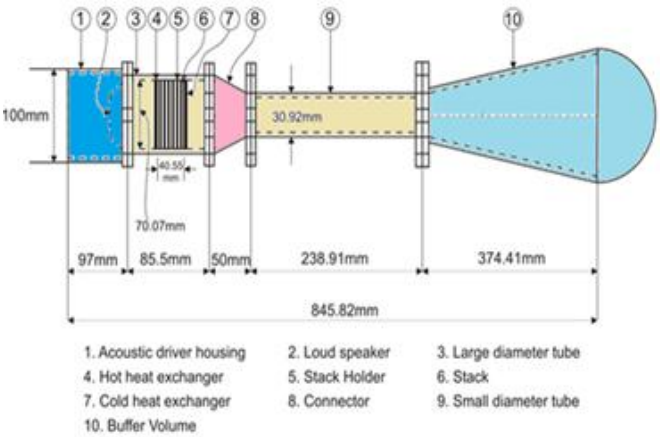

Figure 1: Schematic diagram of thermo-acoustic refrigerator

3. RESULTS AND DISCUSSION

The performance characteristics of the thermoacoustic refrigerator was evaluated based on the input power to the acoustic driver, cooling power and temperature difference for different operating parameters like heating load and frequency. The electrical energy is converted to acoustic power in the acoustic driver. Coefficient of Performance and Relative Coefficient of Performance were used to measure the performance characteristics of thermoacoustic refrigerator.

3.1 Validation

Experimental results obtained from the tests were compared with the DELTA-EC results to find the performance characteristics of thermoacoustic refrigerator as depicted from Figure 2 to Figure 13. It was observed from the figures that both the experimental and DELTA-EC results have the similar trend for all the conditions compared. The experimental results deviated from the DELTA-EC results were due to the viscous effects, discontinuities, turbulence present in the refrigeration system and heat loss from the resonator tube.

3.2 Effect of Temperature difference (ΔT)

Figure 2 to Figure 5 shows the effect of frequency on the variation of the temperature difference. It was found that the difference in temperature increases with an increase in frequency across the hot and cold ends of the parallel plate stack. The interrelation between the operating frequency and natural resonance frequency is the main reason to change in temperature difference between the hot end and cold end of the parallel plate stack.

The performance of the thermoacoustic refrigerator depends on the thermoacoustic process inside the parallel plate stack. How the heat is transferred efficiently from cold end of the heat exchanger to the stack and from the stack to the hot end of the heat exchanger.

It was also found from both the experimental and DELTA-EC results that the temperature difference increases from 200 Hz to 400 Hz and decreases after 400 Hz due to the existence of sound energy which makes resonator to vibrate. The system will not be able to sustain because of higher input power of the loud speaker (acoustic driver). The viscous losses increase and thermoacoustic effect decreases due to the existence of weak thermal penetration depth in the stack at higher operating frequencies.

The magnitude of the temperature difference between the hot end and cold end of the parallel plate stack was found 30.6°C for DELTA-EC model compared to experimental results of 22.5°C at 2 watts heating load, 400 Hz frequency and 2% DR corresponding to a pressure of 10 bar.

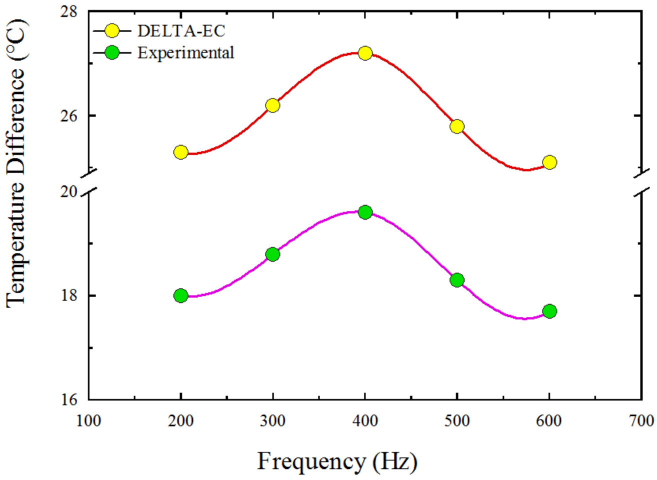

Figure 2: Temperature difference versus Frequency for 2W heating load and 1.6% DR

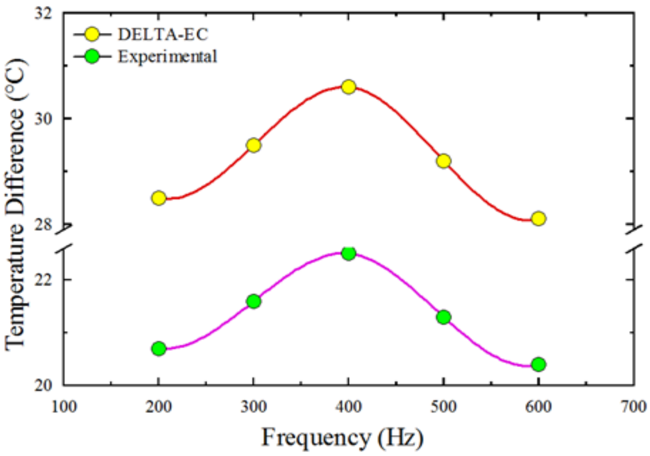

Figure 3: Temperature difference versus Frequency for 2W heating load and 2% DR

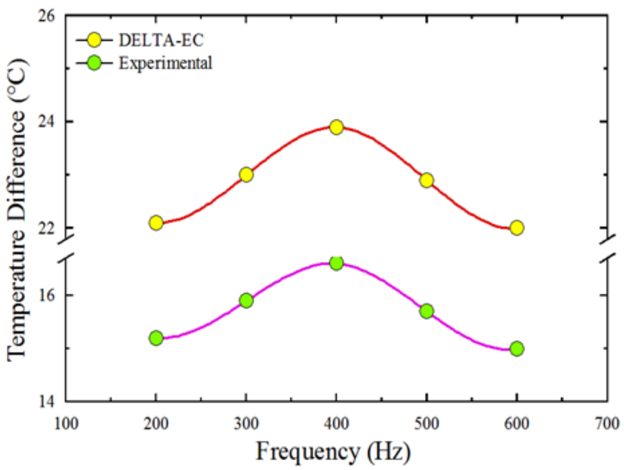

Figure 4: Temperature difference versus Frequency for 10W heating load and 1.6% DR

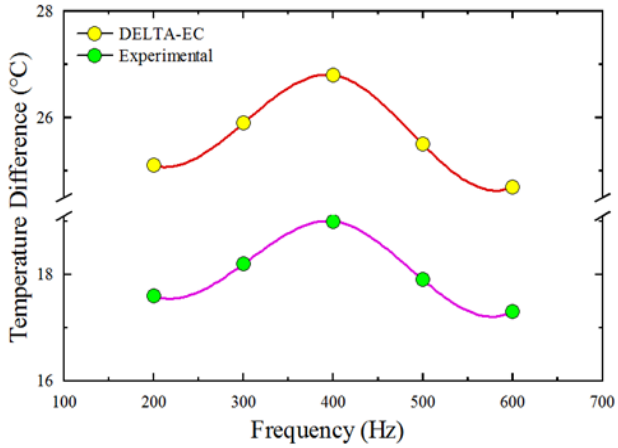

Figure 5: Temperature difference versus Frequency for 10W heating load and 2% DR

By considering Figure 6 and Figure 7, it represents the effect of heating load on the temperature difference for 10 bar pressure and 400 Hz Frequency. The temperature difference depends on the dynamic pressure, heating load, frequency and drive ratio. Three drive ratios are used to measure the temperature difference across the stack using helium as the working substance. The temperature difference increases with an increase in drive ratio due to better viscous and thermal penetration depth as the spacing between the plates in the stack is very small. The drive ratio plays an important role in increasing the thermoacoustic effect leading to better heat transfer and temperature difference. The acoustic power supplied to the acoustic driver is sufficient to eliminate the heat produced at cold end of the parallel plate stack for lower heating loads and it is not sufficient to eliminate the heat produced at higher heating loads due to low electroacoustic energy conversion efficiency of the acoustic driver. The temperature difference for DELTA-EC model across the stack is more compared to experimental results at 2 watts heating load and 2% DR at 400 Hz frequency.

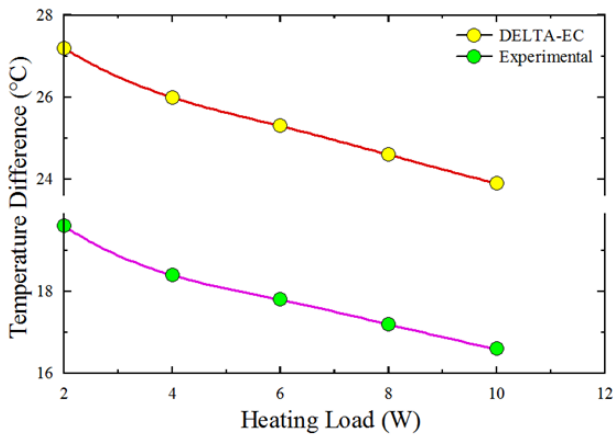

Figure 6: Temperature difference with heating load for 400 Hz frequency and 1.6% DR

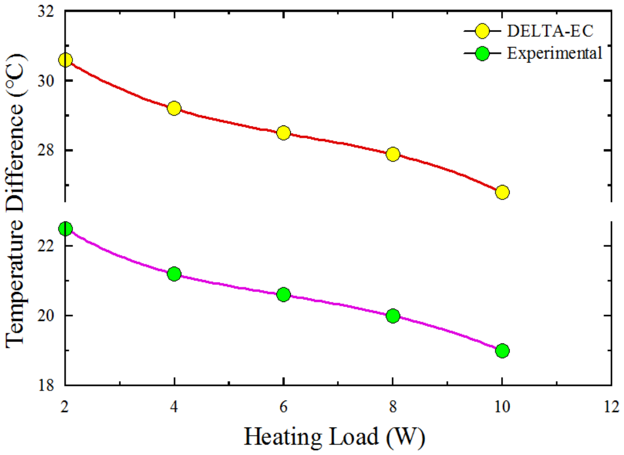

Figure 7: Temperature difference with heating load for 400 Hz frequency and 2% DR

3.3 Effect of Coefficient of Performance (COP)

From Figure 8 and Figure 9, it represents the effect of heating load on COP for different drive ratios. COP is proportional to the heating load and is increases with an increase in heating load. It has been observed from both the experimental and DELTA-EC results that the COP is more in lesser drive ratio and less in higher drive ratio due to the effective thermal penetration depth in the stack and increase in acoustic power input. This leads to efficient removal of heat at cold end of the parallel plate stack. It was found that the COP of DELTA-EC is 2.598 and COP of the experimental results is 2.205 for 10 watts heating load at DR of 1.6%. COP of DELTA-EC model is more compared to COP of the experimental results.

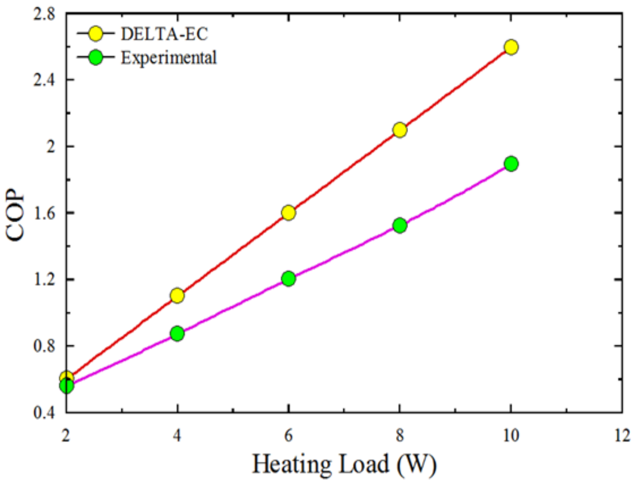

Figure 8: Variation of COP with heating load for 400 Hz frequency and 1.6% DR

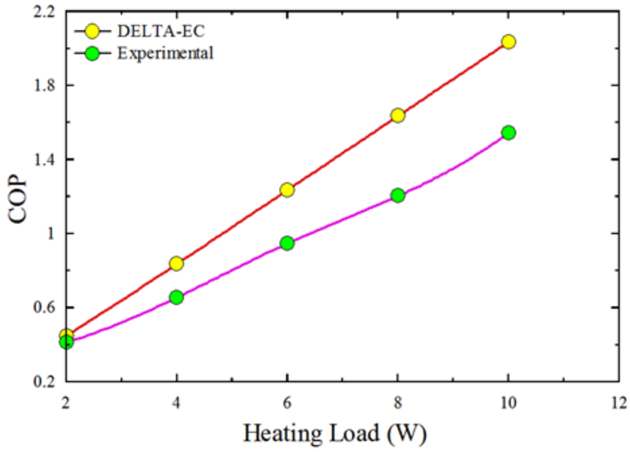

Figure 9: Variation of COP with heating load for 400 Hz frequency and 2% DR

3.4 Effect of Relative Coefficient of Performance (COPR)

Figure 10 and Figure 11 represents the effect of frequency with COPR for parallel plate stack using helium as the working substance. COPR is proportional to COP. It was observed from the figures that the COPR is maximum due to the spacing of the stack plates, viscous and thermal penetration depth on the performance of the thermoacoustic refrigerator. The COPR increases with an increase in COP and this was observed from both the experimental and DELTA-EC results that COPR is maximum at 400 Hz frequency having a drive ratio of 1.6% with 10 watts heating load for a pressure of 10 bar. This was occurred due to the weak thermal penetration depth at high operating frequency in the stack by which there is decrease in thermoacoustic effect and increase in the viscous loss. COPR for DELTA-EC is 0.336 and COPR for experimental results is 0.275.

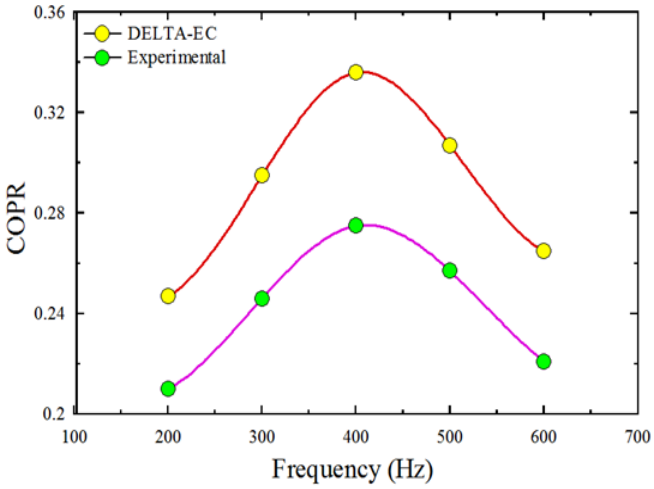

Figure 10: COPR versus Frequency for 10W heating load and 1.6% DR

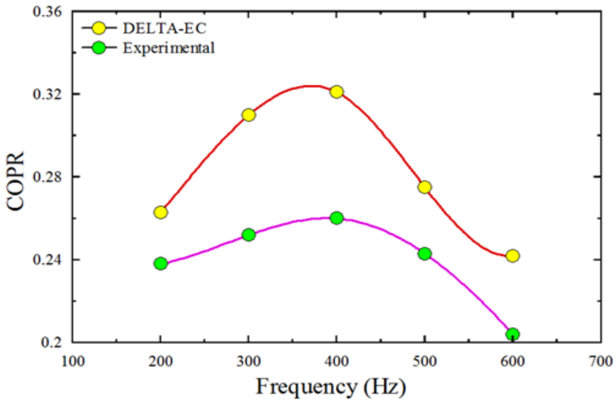

Figure 11: COPR versus Frequency for 10W heating load and 2% DR

Figure 12 and Figure 13 indicates the effect of heating load on COPR for 400 Hz frequency. COPR increases with an increase in heating load for a frequency of 400 Hz at 10 bar pressure for all the drive ratios varies from 1.6% to 2%. Less amount of energy loss took place due to flow discontinuities and turbulence in the resonator at high velocities.

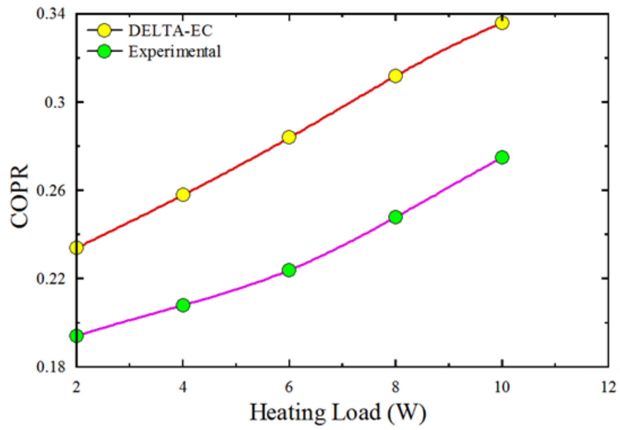

Figure 12: COPR with heating load for 400 Hz frequency and 1.6% DR

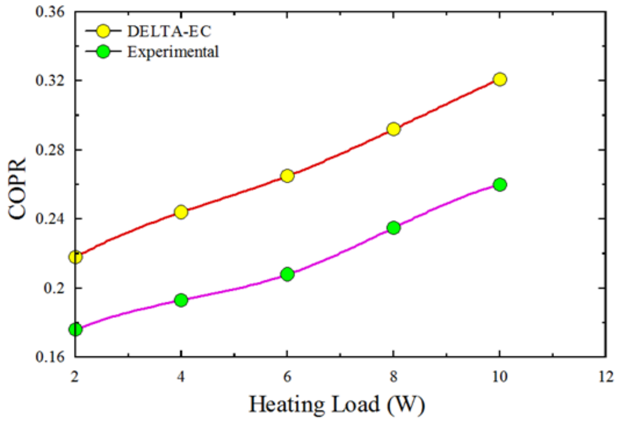

Figure 13: COPR with heating load for 400 Hz frequency and 2% DR

4. CONCLUSIONS

Tests were conducted to estimate the effect of thermoacoustic parameters on the performance characteristics of the thermoacoustic refrigerator for various operating parameters.

- The maximum temperature difference achieved was 22.5°C and 30.6°C for experimental and DELTA-EC model with parallel plate stack using helium as the working substance corresponding to a 2W heating load at 400 Hz frequency for 2% DR of 10 bar mean pressure.
- The COP obtained was 2.205 and 2.598 for experimental and DELTA-EC model with parallel plate stack using helium as the working substance corresponding to a 10W heating load at 400 Hz frequency for 1.6% DR of 10 bar mean pressure.
- The COPR obtained was 0.275 and 0.336 for experimental and DELTA-EC model with parallel plate stack using helium as the working substance corresponding to a 10W heating load at 400 Hz frequency for 1.6% DR of 10 bar mean pressure.
- The experimental results were compared with DELTA-EC model. It was found that experimental and DELTA-EC results have the similar trend for all the parameters.
- It was also noted that the experimental results deviate from that of the DELTA-EC results at about 26% due to the flow discontinuities, turbulence and viscous effects present in the system in addition to conduction heat losses from the surface of the resonator tube.

REFERENCES

[1] Swift, Gregory W., Thermoacoustic engines and refrigerators, Physics today, 1995, 48, 7.

[2] Rott, Nikolaus, Thermoacoustics in Advances in applied mechanics, 1980, 20, 135-175.

[3] Worlikar, Aniruddha S., and Omar M. Knio, Numerical simulation of a thermoacoustic Refrigerator: I. Unsteady adiabatic flow around the stack, Journal of Computational Physics, 1996, 127, 424-451.

[4] Worlikar, Aniruddha S., Omar M. Knio, and Rupert Klein, Numerical simulation of a Thermoacoustic refrigerator: II. Stratified flow around the stack, Journal of Computational Physics, 1998, 144, 299-324.

[5] Worlikar, Aniruddha S., Numerical study of oscillatory flow and heat transfer in a loaded thermoacoustic stack, Numerical Heat Transfer: Part A: Applications, 1999, 35, 49-65.

[6] Tijani, M. E. H., J. C. H. Zeegers, and A. T. A. M. De Waele, Design of thermoacoustic refrigerators, Cryogenics, 2002, 42, 49-57.

[7] Tijani, M. E. H., J. C. H. Zeegers, and A. T. A. M. De Waele, Construction and Performance of a thermoacoustic refrigerator, Cryogenics, 2002, 42, 59-66.

[8] Tu, Qiu, V. Gusev, Michel Bruneau, Chunping Zhang, Ling Zhao, and Fangzhong Guo, Experimental and theoretical investigation on frequency characteristic of loudspeaker-driven thermoacoustic refrigerator. Cryogenics, 2005, 45, 739-746.

[9] Penelet, Guillaume, Vitalyi Gusev, Pierick Lotton, and Michel Bruneau, Experimental and theoretical study of processes leading to steady-state sound in annular thermoacoustic engines, Physical Review E, 2005, 72, 016625.

[10] Nsofor, Emmanuel C., and Azrai Ali, Experimental study on the performance of the Thermoacoustic refrigerating system, Applied Thermal Engineering, 2009, 29, 2672-2679.

[11] Bheemsha, Ramesh Nayak. B., Pundarika.G, Design and optimization of a Thermoacoustic refrigerator, International Journal of Emerging Trends in Engineering and Development, 2011, 2, 47-65.

[12] Tasnim, S. H., S. Mahmud, and R. A. Fraser, Effects of variation in working fluids and Operating conditions on the performance of a thermoacoustic refrigerator, International communications in heat and mass transfer, 2012, 39, 762-768.

[13] Kamble, Bharatbhushan V., Biju T. Kuzhiveli, S. Kasthurirengan, and Upendra Behera, Experimental and simulation studies on the performance of standing wave thermoacoustic prime mover for pulse tube refrigerator, International journal of Refrigeration, 2013, 36, 2410-2419.

[14] Antao, Dion Savio, and Bakhtier Farouk, Numerical and experimental characterization of the inertance effect on pulse tube refrigerator performance, International Journal of Heat and Mass Transfer, 2014, 76, 33-44.

[15] Ramesh Nayak. B., Bheemsha, Pundarika.G, Performance evaluation of Thermoacoustic refrigerator using air as working medium, SSRG International Journal of Thermal Engineering, 2015, 3, 1-7.

[16] Nayak, B. Ramesh, G. Pundarika, and Bheemsha Arya, Influence of stack geometry on the performance of thermoacoustic refrigerator, Sadhana, 2017, 42, 223-230.

[17] Nekrasova, S. O., E. A. Zinovyev, and A. I. Dovgyallo, Numerical investigation on a 70 Hz pulse tube micro-cryocooler, Procedia Engineering, 2016, 152, 314-320.

[18] Saechan, Patcharin, and Artur J. Jaworski, Thermoacoustic cooler to meet medical storage needs of rural communities in developing countries, Thermal Science and Engineering Progress, 2018, 8, 164-175.

[19] Fatimah A. Z. Mohd Saath., Ernie Mattokt., Sitti H. A. Mustaffa., and Normah Mohd Ghazali, Numerical study of turbulence related to vortex shedding structure of an oscillatory flow in thermoacoustic energy system, Energy Procedia, 2019, 156, 239-243.

[20] Saechan, Patcharin, and Isares Dhuchakallaya, Design and experimental evaluation of a travelling wave thermoacoustic engine, Energy Reports, 2020, 6, 1456-1461.

[21] Chaiwongsa Praitoon, and Somchai Wongwises, Effect of the blockage ratios of circular stack on the performance of the air-based standing wave thermoacoustic refrigerator using heat pipe, Case Studies in Thermal Engineering, 2021, 24, 100843.