Computational Investigation on the performance of thermo-acoustically driven pulse tube refrigerator

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Abstract: A Thermoacoustic Pulse Tube Refrigeration (TAPTR) system employs a thermo acoustic engine as the pressure wave generator instead of mechanical compressor. Such refrigeration systems are highly reliable due to the absence of moving components, structural simplicity and the use of environmental friendly working fluids.
In the present work, a traveling wave thermoacoustic primmover (TWTAPM) has been developed and it is coupled to a pulse tube cryocooler. The performance of TAPTR depends on the operating and working fluid parameters. Simulation studies of the system has been performed using ANSYS Fluent and compared with experimental results.

Keywords:Thermoacoustics, Traveling Wave, Prime mover, CFD, Pulse Tube Refrigeration

I. Introduction

The heat interaction between an acoustic wave and the solid surface that possess a temperature gradient within the so-called ‘‘thermal penetration depth” is termed as thermoacoustic effect. Thermoacoustic technology receives interest in recent research due to the advantages such as absence of moving parts and the possibility of using renewable energy for its operation

Thermoacoustic technology has witnessed a rapid development in recent years. Devices such as thermoacoustic engine, thermoacoustic refrigerator and thermo acoustically driven pulse tube cryocoolers are the outcomes of this technology. Thermoacoustic engines convert thermal energy into acoustic energy in the form of high amplitude sound waves. This acoustic power is used to drive thermoacoustic pulse tube cryocooler or thermoacoustic refrigerators .

Thermoacoustic effect was firstly described by Lord Rayleigh in his famous book “ The theory of sound”. He explains the production of thermoacoustic oscillations as “if heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction, the vibration is encouraged”. The process can also be reversed and then the produced acoustic wave can generate a temperature gradient [1].

Ceperley [2] showed that a traveling acoustic wave propagating through a regenerator undergoes a thermodynamic cycle similar to that of the Stirling cycle. Yazaki et al. [3] constructed a pure TWTAPM which demonstrated better performance than the standing wave thermoacoustic primemover. Due to the large viscous losses associated with high acoustic velocities there were reduction in the efficiency. Backhaus and Swift [4] made improvements on the traveling wave prime mover by adding a resonator in the loop, so that traveling wave phasing could be obtained hence increasing the efficiency.

Qiu et al. [5] studied the traveling wave engine driven double inlet pulse tube and they observed that for better performance of the pulse tube occurs at low frequency and high pressure amplitude.

Nijeholt et al. [6] has carried out the CFD analysis of the traveling wave thermoacoustic engine using Ansys CFX to study the nonlinear phenomena of the system. Zink et al. [7] performed the CFD analysis of a whole thermoacoustic engine and has presented the influence of a curved resonator on the thermoacoustic effect. Mathew Skaria et al. [8] had done the CFD analysis on traveling wave thermoacoustic prime mover towards the development of pulse tube cryocoolers.

We present the simulation studies on the traveling wave thermoacoustic primemover by varying the working fluid and the operating pressure. The output from the thermoacoustic primemover are taken as the input to the Pulse tube refrigerator simulation.The results are comparedwith experimental results

2. Experiment Setup

The experimental set up of the TAPTR is shown in Figure.1. The system includes pulse tube refrigerator and traveling wave thermoacoustic primemover. The traveling wave thermoacoustic primemover includes a feedback loop and resonator tube with the buffer. The loop portion includes heater, ambient heat exchanger, regenerator made of stainless steel wire mesh, cold heat exchanger, and the compliance tube. The heater provides heat to the hot heat exchanger and the cold heat exchanger extracts heat from the other end of the stack. This creates a temperature gradient across the stack, which generates thermoacoustic oscillations. The traveling wave loop is also attached with a resonator tube with the buffer.

The traveling wave feed back loop and the resonator are made of stainless tube of 50mm inner diameter. The heat exchangers made by using copper which have 0.5 mm plate thickness and 1mm plate spacing. Regenerator prepared by using stainless steel wire mesh which placing several round steel wires mesh one above the other to form a cylindrical shape.

The zone of hot heat exchanger is heated by external resistance wire heating element of 1kW. The heaters are insulated with several layer of ceramic wool to minimize the loss of heat to the surroundings. The temperature control unit and variable output voltage transformer are used to control the input power to the heater. The ambient heat exchanger is provided with water jacket and cooling water is supplied to remove the heat so as to maintain it at ambient temperature. To pickup pressure amplitude and to connect the pulse tube refrigerator holes are provided at several location of the primemover. Figure 2 shows the Schematic of TWTAPM .

The Pulse tube refrigerator (PTR) consists of aftercooler, regenerator, cold heat exchanger, pulse tube, hot heat exchanger, orifice tube and surge volume. Heat exchangers are made of copper and the regenerator made by stainless steel. Figure 3. shows the photograph of Pulse Tube Refrigerator and its schematic is shown in figure 4.

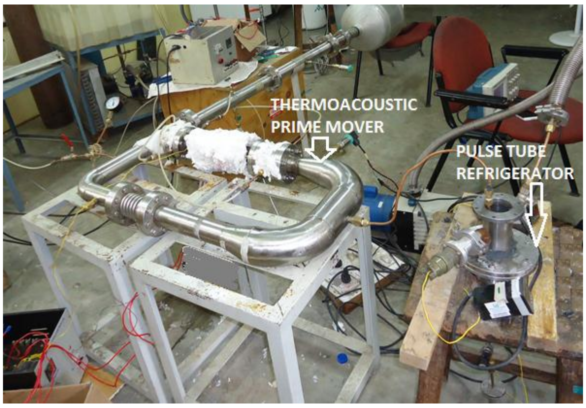

Figure.1. Photograph of thermoacoustically driven Pulse Tube Refrigerator

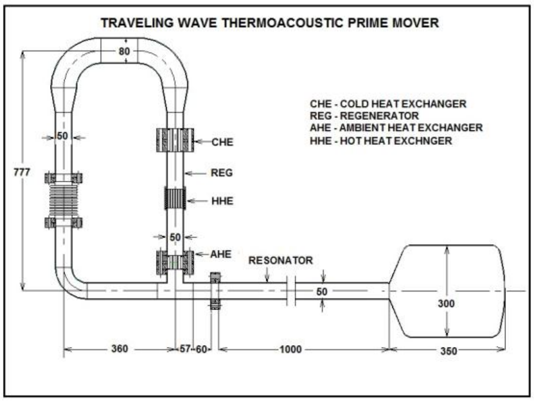

Figure.2. Schematic of TWTAPM

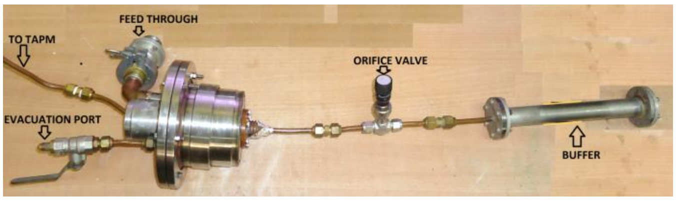

Figure 3. Photograph of Pulse Tube Refrigerator

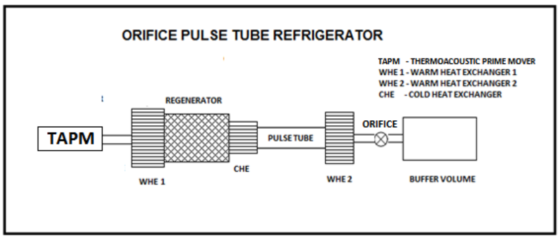

Figure 4. Schematic of the TAPTR

3. Simulation Using Cfd

3.1 CFD simulation of TWTAPM

In the CFD analysis of above TWTAPM, the stack (regenerator) is modeled as a stainless steel porous media with porosity of 0.67 as per the experimental conditions. The system had the regenerator and resonator lengths of 105 mm and 1 m respectively. In place of modeling the hot and the cold heat exchangers, a User Defined Function (UDF) is defined over the regenerator length which in turn reduces the computational time and the number of cells. The UDF is a C program expressing the linear temperature variation from the hot end of the stack to its cold end. The hot end and cold end temperatures were chosen to be 1050K and 350K respectively. The grid was built using triangular pave cells. The condition of simulation for TWTAPM same as given in reference [8].

3.2 CFD simulation of Pulse Tube Refrigerator

The geometrical model and the meshing of the geometry of pulse tube refrigerator is created in ANSYS Workbench software.The details of geometry and boundary conditions for CFD simulations are presented in Table 1 and Table 2

In the present case the thermoacoustic Pressure wave which is essential to drive the pulse tube is provided by the UDF at the inlet of after cooler section of pulse tube refrigerator.The User Defined Function (UDF) is developed in C programming language and the oscillatory sine wave is created by using the equation $A_n \, Sin(\omega t)$. Where 'A_n' is pressure amplitude and '**ω**' is angular velocity which is calculated by using equation $\omega=2\pi f$. The frequency and pressure amplitude for the program is taken from experimental data corresponding to system operating pressure.

Since every component of the PTR system is in fact cylindrical in shape and all the components are aligned in series to form an axisymmetric system.The 2-dimensional axisymmetric geometry the system was created using ANSYS workbench.

Initially the entire geometry was created as single component then it is splited in different zones. The function of splitting is to divide the geometry as different components so as to enable to set different boundary conditions at different zones as needed. The Figure 5 shows the view of the axisymmetric geometry of the PTR. The model created was then exported to FLUENT and defined the boundary conditions. Figure 6 dipicts the mesh near the pulse tube section of PTR.

Figure 5 Two dimensional axisymmetric geometry of PTR using workbench

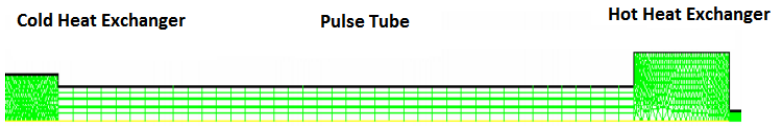

Figure 6 Axi symmetric two dimensional mesh of PTR near the pulse tube section

Table.1.Component dimensions of PTR

Sl.No.	Component	Radius (m)	Length (m)
1	After cooler	6.25e-03	15e-03
2	Regenerator	6.25e-03	50e-03
3	Cold heat exchanger	3.5e-03	3e-03
4	Pulse tube	3.5e-03	40e-03
5	Hot heat exchanger	6.25e-03	15e-03
6	Orifice tube	2.5e-03	300e-03
7	Surge Volume	15e-03	215e-03

Table.2.Shows the the boundary and initial condition of PTR

Component	Condition
Aftercooler wall	295K
Regenerator wall	Adiabatic
Cold heat exchanger wall	Adiabatic
Pulse tube wall	Adiabatic
Hot heat exchanger wall	295K
Orifice tube wall	Adiabatic
Surge Volume wall	Adiabatic
Viscous resistance(m^{-2})	9.44e+09
Inertial resistance(m^{-1})	76090

4. Results and Discussion

Figure 7 shows the variation of resonace frequency with average pressure.The resonance frequency of the traveling wave system depends on the working fluid used.From the figure it is clear that the resonance frequency is nearly constant with variation of average pressure of the working fluid. The reason is that frequency of ocillation for traveling wave thermoacoustic prime mover is directly propotional to speed of sound in paticular working gas. It is expressed as f= a/4L, where 'a' is speed of sound which is given by, $a = \sqrt{\gamma\left(\frac{P}{\rho}\right)}$. Increasing the operating pressure correspondingly increases the density of the working fluid in the system. So the ratio of working pressure and density remains nearly constant. Hence, the frequency of oscillation is nearly constant with the increase in working pressure.

Also it is observed from Figure 7 that the frequency is low for argon and high for helium . This can be understood as follows. The density of gas within a constant volume varies accordingly to its molecular weight. The molecular weight of helium is low and for argon it is more.Thus the sound velocity decreases in the order helium and argon and hence the frequency of oscillations.

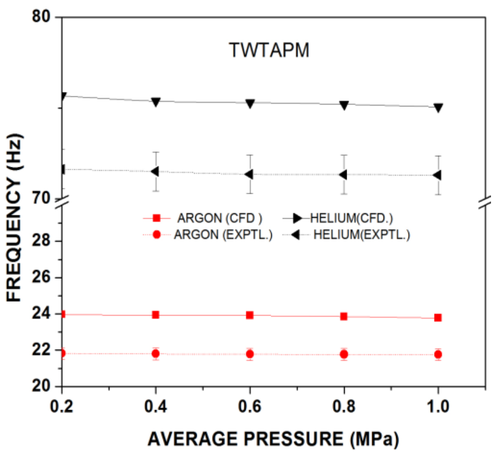

Figure 7 variation of resonace frequency with average pressure

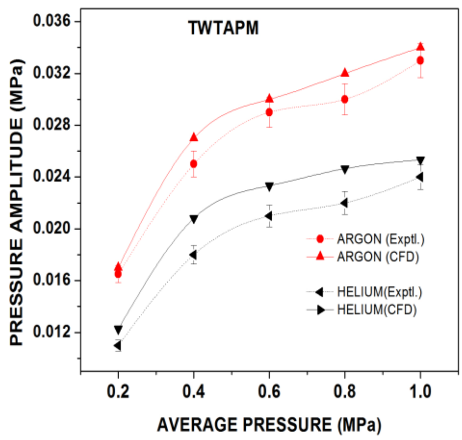

Figure 8 variation of pressure amplitude with average pressure.

Figure 8 plots the oscillation pressure amplitudes as a function of average pressure of TAPM for different pure working fluids. It is observed that the measured pressure amplitudes increase with the increasing pressure of the working fluid. This is also predicted by the simulation. This can be attributed as, according to linear thermoacoustics (Swift, 1988) the momentum, continuity and energy equations the pressure amplitude is directly proportional to velocity amplitude by the inertance and viscous resistance. Both inertance and viscous resistance of working gas depend upon the mean density of working gas in the system. As the operating pressure of the working gas in the system increased, the density increases correspondingly which leads to the increase in pressure amplitude.

Also it is observed from graph at the pressure amplitudes are the highest for argon, the lowest for helium . This is because the pressure amplitudes depend on the density of the working gas, and as higher the molecular weight, higher the density causes highest pressure amplitude for argon as working fluid and lowest for helium due to its lowest density.

In the present CFD simulation of the TAR, the pressure wave output fron the TWTAPM is provided at the inlet of the after cooler of PTR by a user defined function. Figure 9 shows the pressure input wave form at the after cooler for Argon at 0.7MPa. For this condition a cold temperature of ~266K was obrained. For Helium,using the pressure input wave form for Helium a cold temperature of ~ 271K was obrained.

Figure 11 shows the variation of temperature with average pressure.Since pressure amplitude increases with increase in average pressure,more heat pumping is possible at the pulse tube ,which results in lower cold end temperature of PTR.

Figure 12 shows the variation of cold end temperature with porosity of regenerator.It is observed that variation of porosity of the regenerator changes the cold end temperature.The cold end temperature decreases with increase in porosity to an optimum value and then increases.

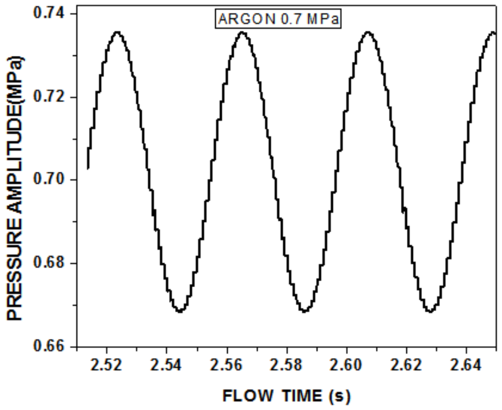

Figure 9. The pressure input wave form at the after cooler for Argon at 0.7MPa

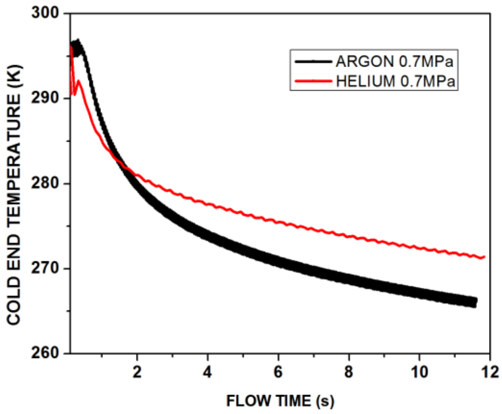

Figure 10. Variation of temperature with CFD flow time

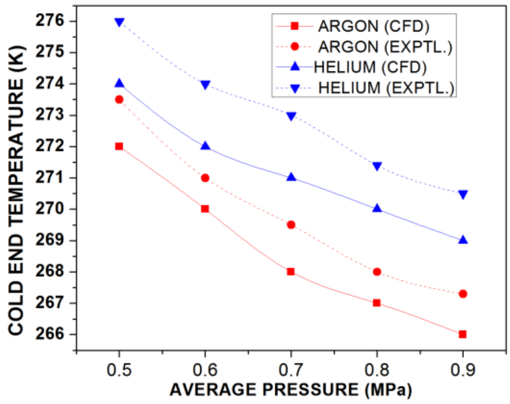

Figure 11. Variation of temperature with average pressure

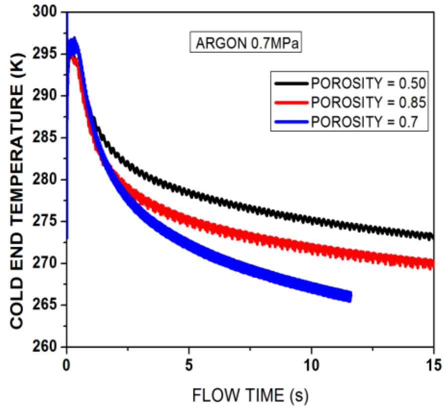

Figure 12. Variation of temperature with porosity of regenerator

5. Conclusion

The CFD analysis has been carried out for TAPTR driven by TWTAPM. The analysis is done different working fluids namely helium and argon at different average pressures. The results are compared with the experimental results. The CFD analysis indicates the following.

- the working fluid always plays major role in deciding the operating frequency and the pressure amplitude in the system.
- argon shows the lowest frequency and the highest amplitude, which is also observed experimentally.
- For all the working fluids investigated, with the average pressure increase, the pressure amplitude also increases with minor changes in frequency.
- Among Helium and Argon, the lowest cold end temperature was observed for Argon.
- Cold end temperature at the pulse tube decreases with increase in average pressure due to increase in pressure amplitude.
- increase in the porosity of the regenerator causes change in cold end temperature and there exists an optimum porosity.
- The predictions of CFD are fairly in agreement with the experimental studies conducted on these systems.

6. References

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