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SIMULATION STUDIES ON THE THERMOACOUSTIC COOLING

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ABSTRACT

Cooling by an acoustic wave is one of the attractive areas of research in the field of cryo coolers and refrigeration. Towards the development of such systems, simulation can be carried out by several methods. We present here the simulation studies of thermo acoustically driven standing wave refrigerator and traveling wave thermoacoustic prime mover for the pulse tube refrigeration using the procedures of Computational Fluid Dynamics (CFD). The CFD analysis is carried out using Ansys Fluent, incorporating the necessary boundary conditions, for different operating and geometric parameters. The study indicates that the working fluid has an influence on the system frequency and on the pressure amplitude. The results obtained by CFD are compared with those obtained using experiments wherever possible and they are in good agreement.

Key words: CFD, Primemover, Standing Wave, Thermoacoustics, Traveling Wave.

1. INTRODUCTION

Thermoacoustic technology has gained considerable attention in recent years due to inherent reliability, structural simplicity, absence of moving parts, and uses environmentally friendly working fluids like Helium, Argon, Nitrogen etc. Such thermoacoustic systems have a strong potential to replace conventional refrigeration systems. The basic principle which governs the operation of these thermoacoustic devices is the “thermoacoustic effect”, which results from thermodynamic interaction between a compressible fluid and solid surface.

The energy interactions can be utilized for designing useful devices that convert high amplitude sound waves into temperature gradient and viceversa. The thermoacoustic system that converts heat energy into acoustic energy is called a thermoacoustic prime mover while a system that converts acoustic energy into temperature difference is called a thermoacoustic refrigerator. According to the type of sound wave, thermoacoustic devices can also be categorized as standing wave and travelling wave systems. A standing wave thermoacoustic device typically uses the stack and it is a solid component with pores that allow the working fluid to oscillate while in contact with the solid walls. The oscillation of the gas is caused or accompanied with the change of its temperature.

A travelling wave thermoacoustic system consists of a resonator tube and a loop which contains a regenerator and heat exchangers. The regenerator is a porous medium with a high heat capacity. As the gas flows back and forth through the regenerator it periodically stores and takes up heat from the regenerator material.

Hofler, et al. [1] invented a standing-wave thermoacoustic refrigerator in which the coupled oscillations of gas motion and heat transfer in the sound wave are phased so that heat is absorbed at low temperature and waste heat is rejected at higher temperature.

Ceperley [2] was the first to realize that a traveling acoustic wave propagating through a regenerator undergoes a thermodynamic cycle similar to the Stirling cycle. In such systems the acoustic waves generated have the phase angle between the pressure and velocity close to zero in the regenerator.

In order to optimize the performance of thermoacoustic system, analysis of the system can be done using various tools. In the present paper, simulation studies using CFD on thermoacoustically driven standing wave thermoacoustic refrigerator and traveling wave thermoacoustic prime mover for driving pulse tube coolers were explained.

2. PROBLEM SPECIFICATION AND GEOMETRIC MODELING

2.1 Thermoacoustically driven standing wave refrigerator

The thermoacoustically driven standing wave refrigeration system selected for study consists of prime mover stack of stainless steel, refrigerator stack made of stainless steel, resonator, copper heat exchangers and buffer. The prime mover of the system consists of stack placed in between the hot and cold heat exchanger and it acts as the acoustic driver for the refrigerator. The temperature gradient over the plates was maintained by using electrical heater mounted over the hot end heat exchanger and by circulation of water over the cold heat exchanger. Fig. 1 shows the experimental set up and Fig. 2 shows the schematic of thermoacoustic refrigerator or. The refrigerator stack is made out of stainless steel placed in between the copper heat exchangers. The spacing between the plates of prime mover stack and refrigerator stack are 1mm and 0.5mm respectively and plate thickness is 0.5mm. The dimensions of the various components are shown in Table 1.

Fig.1. Thermoacoustically driven standing wave thermoacoustic refrigerator experimental setup.

Fig.2. The schematic of the Thermoacoustically driven standing wave thermoacoustic refrigerator

TABLE 1. Dimensions of thermoacoustically driven standing wave refrigerator

System	Parameter	Hot Heat Exchanger(mm)	Cold Heat Exchanger(mm)	Stack(mm)
Prime mover	Diameter	51	51	51
	Length	60	40	200
Refrigerator	Diameter	51	51	51
	Length	10	10	57

In the system, the prime mover is located 200 mm away from closed end and the refrigerator stack is placed 47 mm away from the cold end heat exchanger of the prime mover. At the end of the resonator, a buffer of 300 mm diameter and 350 mm length is attached. The computational domain consists of prime mover plates placed at 400mm from closed end and refrigerator plates placed at 87 mm from the primemover. The modeling and meshing of the above system was done using GAMBIT software.

2.2 Traveling wave thermoacoustic prime mover for pulse tube cooler

In the traveling system the core element is the regenerator which is placed inside the loop of the traveling wave engine. For the present CFD analysis since no adequate experimental data was not available from our traveling wave thermoacoustic prime mover, we have selected the experimental results of Chen et.al [3]. In the two-dimensional CFD simulation the regenerator was modeled as a porous media (stainless steel) with porosity of 0.67 as per the experimental studies. The system had the regenerator and resonator lengths of 43 mm and 1m respectively.

Fig.3. The Schematic of the traveling wave thermoacoustic primemover

Fig.4. The simulation model of the traveling wave thermoacoustic primemover

Instead of modeling hot and 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 hot end and cold end temperatures were chosen to be 1050K and 350K respectively. The grid was built using triangular pave cells. Fig.3 shows the schematic and Fig. 4 shows the and computational domain chosen for CFD analysis.

3. CONDITIONS OF SIMULATION FOR THERMOACOUSTIC SYSTEMS

The two dimensional transient simulation was performed for both systems. The boundary conditions for the simulations are chosen as the same as that followed by Zink et al. [3]. The turbulence model selected is k- ϵ model, since it is valid for a wide range of flows. The discretization for all flow variables is chosen to be of second order for increased accuracy. Pressure is discretized with the PRESTO! scheme for increased accuracy of flow in the channel. The time step for the transient simulation was chosen to be 1E-5. The stack walls/regenerator are set with a linear temperature gradient using the User Defined Function (UDF) to avoid the complexity in using the heat exchangers. The solver properties are taken as pressure based, Green Gauss Node Based, with physical velocity for porous formulation

4. RESULTS AND DISCUSSION

4.1 Thermoacoustically driven standing wave refrigeration system

The CFD analysis of the system was done for different resonator length using Helium gas at 2 bar operating pressure and the stable thermoacoustic oscillations obtained are shown in Fig. 5. It is observed that with increase in resonator length both the frequency of oscillation and pressure amplitude decreases. This due to the acoustic losses in resonator. Table 2 shows the effect of resonator length on temperature difference across the stack. The lowest temperature is observed for a resonator length of 1m and as resonator length increases, the temperature on cold end of refrigerator increases. Fig. 6 shows the influence of working fluid (Helium and Nitrogen) on the system on frequency and pressure amplitude for resonator length of 1m and at 2 bar operating pressure. Among Helium and Nitrogen, Helium shows highest frequency and low amplitude. This is due to the fact that the frequency of oscillation is directly proportional to speed of sound in a particular working gas. Also the molecular weight of Nitrogen is high on comparison with Helium. For better refrigeration high frequency and high amplitude is desirable. The temperature variation across the refrigerator stack for different working fluids is shown in Tables 2. Helium shows highest temperature difference than Nitrogen across the refrigerator stack. Fig. 7 shows the temperature contour at the refrigerator stack. An experimental study conducted with Helium gas at 2 bar pressure with 1m resonator length predicts a lowest temperature of 296K at cold heat exchanger and it is comparable with CFD results.

TABLE 2. CFD results of thermoacoustically driven refrigerator for different resonator length

length	frequency	Pressure amplitude	Mean temperature		DeltaT
			Hot heat exchanger	Cold heat exchanger	
1m	160	25000	307	295	12
1.5m	130	18000	306	296	10
2m	114	13500	304	298	6

Fig. 5. Stabilized oscillations at different length for helium at 2 bar

Fig. 6. Stabilized oscillations for Helium and Nitrogen at 2 bar for resonator length of 1m

TABLE 3. CFD results of thermoacoustically driven refrigerator for different fluid

GAS	frequency	Pressure amplitude	Mean temperature		DeltaT
			Hot heat exchanger	Cold heat exchanger	
HELIUM	160	25000	307	295	12
NITROGEN	50	31000	305	299	6

Fig.7. Temperature contour across at the refrigerator stack for helium at 2 bar (1m resonator length)

4.2 Traveling wave thermoacoustic prime mover

The two dimensional analysis on the system shows that when the operating pressure increases pressure amplitude also increases, but the frequency is almost same. The variation pressure amplitude for different pressures is shown in Fig. 8. The plot of pressure amplitude and average system pressure (see Fig. 9) shows the comparison of CFD simulation with experimental results by Chen et al. and it agrees well. As the average pressure increases, the pressure ratio also increases. Higher pressure amplitude gives higher energy density. The computational frequency for nitrogen at 5.3 bar mean pressure is 55Hz, where as the experimental frequency is 45Hz.

Fig. 10 shows the pressure waves at different locations (L1, L2, L3, L4, L5 and L6) in the traveling wave TAPM, using nitrogen gas with an average charge pressure 5.3 bar. L1 is located above the cold end heat exchanger, L2 in the middle of compliance tube, L3 at the end of inductance tube and L4 at the inlet of inductance tube, L5 above the ambient heat exchanger and L6 at the end of resonator tube. It can be observed that the pressure oscillations in the loop almost have the same phase but the amplitudes are varying at different location. Along the loop the pressure amplitude decreases from L1 to L5. The system has its maximum pressure amplitude at the regenerator cold end and it is the exact location pulse tube refrigeration system.

Fig.8. Variation of frequency with operating pressure

Fig.9. Comparison of CFD simulation and experimental [4] results

Fig. 10. Pressure oscillations at locations L1,L2,L3,L4,L5andL6 in the travelling wave thermoacoustic prime mover

5. CONCLUSIONS

The computational analysis indicates that.

- For the standing and traveling wave systems, the working fluid always plays a vital role in deciding the operating frequency and the pressure amplitude.
- In both systems Helium shows the highest frequency with the lowest amplitude. For thermoacoustic refrigerator a fluid with high frequency is desirable and for pulse tube cooler a fluid with low frequency is desirable.
- For thermo acoustically driven refrigerators Helium shows better performance than nitrogen.
- In a traveling wave system there is a variation in the pressure amplitude at the torus loop and the pressure amplitude is maximum near the cold end of the regenerator.
- The predictions of CFD are in close agreement with the experimental results.

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