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Influence of Working Fluid and Operating Parameters on the Performance of Traveling Wave Thermo Acoustic Prime Mover

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Abstract— ***The paper present the performance studies on a traveling wave thermoacoustic system developed in our laboratory. Experiments were carried out for different working fluids such as Helium, Argon and Nitrogen and at different operating pressures. The results indicate that the working fluids with different charge pressures are critical to the performance of the system. The above experimental results are compared with simulation (CFD and Delta EC) results wherever possible and they are in good agreement.***

Index Terms— ***Traveling wave, prime mover, working fluid, CFD, Delta EC.***

I. INTRODUCTION

The thermoacoustic technology has become a focus of recent research due to the absence of moving parts, high reliability and structural simplicity. In thermoacoustic systems, the thermal energy is converted into acoustic energy and vice versa. The so called 'thermoacoustic effect' is caused due to the compressible oscillatory gas flow and the heat interaction between a solid material and adjacent gas at the thermal penetration depth. Ceperley[1] in 1979 found that in a looped thermoacoustic prime mover, the heat interaction between the gas and the solid material undergoes a Stirling-like thermodynamic cycle. Later on Backhaus and Swift [2] at the Los Alamos National Laboratory successfully build a highly efficient travelling wave thermoacoustic prime mover using a looped tube with along resonator tube, reducing velocity and therefore friction losses in the loop. Many traveling wave thermoacoustic engines have been built and studied all over the world [3-10] to predict their performances under different conditions

II. THERMOACOUSTIC THEORY

The Travelling Wave Thermoacoustic Prime Mover (TWTAPM) is equipped with two heat exchangers, which produces a temperature gradient on the regenerator between them.

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The spontaneous gas oscillations are amplified at the regenerator and it travels around the loop through the regenerator from cold to hot. In TWTAPM, The oscillating pressure and the velocity of the gas are in phase, which implies that good thermal contact is essential between the gas and the regenerator. The good thermal contact can be obtained by keeping the channel sizes in the regenerator smaller than the thermal penetration depth.

The regenerator resembles the stack but it is with a smaller spacing and the recommended spacing should be between and (Yu et al., 2005). This small spacing is necessary to maintain isothermal conditions between the gas parcels and the adjacent solid material of the regenerator. When gas parcels are displaced within the thermal penetration depth of the regenerator surface, they exchange heat with it.

The characteristic lengths are important in calculating the spacing within the stack or regenerator are the thermal penetration depth and the viscous penetration depth . These parameters indicate the depth of the boundary layer in which heat and momentum can diffuse through though the oscillating gas. The thermal and viscous penetration depths ratio are related by the Prandtl number, describes the extent of the thermoacoustic effects expected from any chosen working fluid.. A lower value for Prandtl number, characteristic of the inert gases, promotes thermoacoustic effects. In a TWTAPM, the thermo physical properties of the working gas affect the operation of the device. Thermo physical properties such as molecular mass, density, thermal conductivity, thermal diffusivity, Prandtl number and specific heat with their variation with temperature and pressure are important for the selection of the working fluid. The paper present the studies on TWTAPM developed in our laboratory. Experiments were carried out for different working fluids such as Helium, Argon and Nitrogen and at different operating pressures. The results indicate that the working fluids with different charge pressures can influence the performance of the system. The above experimental results are compared with simulation (CFD and DeltaEC) results.

III. EXPERIMENTAL SETUP

The experimental system consists of two parts, a feedback loop and resonator with the buffer. The loop portion includes heater, ambient heat exchanger, stack made of stainless steel wire mesh, cold heat exchanger, and the compliance tube.

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The ceramic band heater (1kW) mounted over the hot heat exchanger zone, maintains that zone at elevated temperature and cold heat exchanger is kept at ambient temperature. 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 schematic of the traveling wave thermoacoustic prime mover is shown in Figure 1.

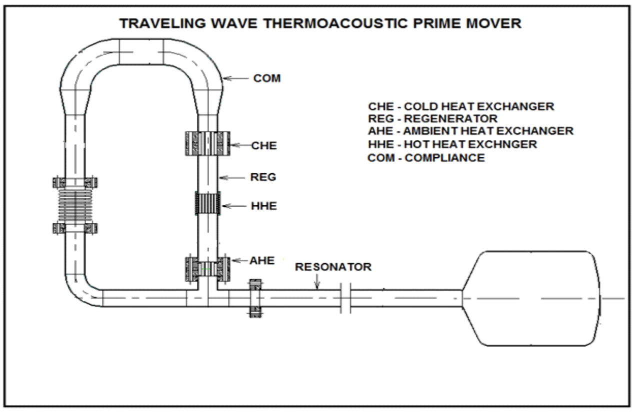

Figure 1 The Schematic of the TWTAPM

The system instrumentation includes pressure transducers, thermocouples, temperature controller, oscilloscope etc. The pressure amplitudes were measured with GEFRON make (model TKDA) pressure transducer and the temperatures at heat exchangers were measured using K-type thermocouples.

Keeping the working fluid at the required pressure within the system, the hot end temperature is increased which causes the gradual increase of temperature difference (ΔT) across the stack. The onset of the oscillations occurs for a ΔT of approximately 600K. With subsequent increase in ΔT, the amplitude increases and becomes nearly constant for a ΔT approximately 700K. Therefore all the experimental studies were carried out at ΔT ~700K, for different working fluids such as Helium, Argon and Nitrogen at varying average pressures. The experimental results are discussed in a later section

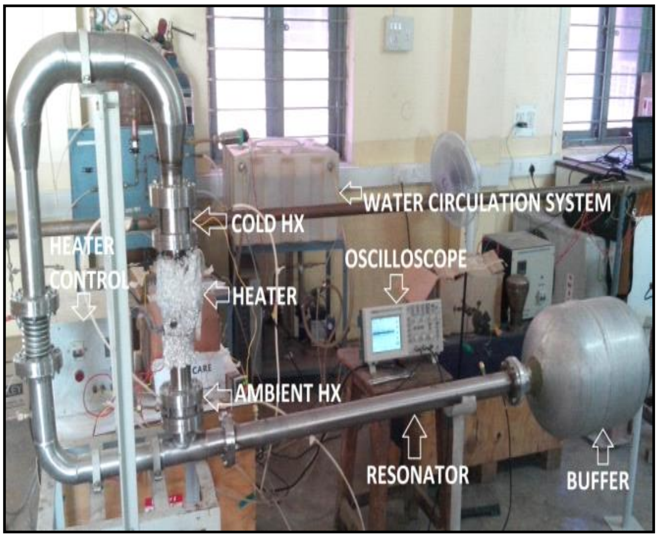

Figure 2 Experimental setup for the TWTAPM

IV. DELTAEC SIMULATION

DeltaEC (Design environment for low amplitude thermoacoustic Energy Conversion) is a computer simulation program developed by Bill Ward and Greg Swift (1994, 2008) in Los Alamos National Laboratory (LANL), USA and is being extensively used by researchers to simulate the performance of the thermoacoustic systems.

The DeltaEC code solves the one dimensional wave equation, continuity and energy equation in a geometry defined by the user as a sequence of acoustic segments such as ducts, compliances, conical sections, and thermoacoustic stacks or regenerators.

V. CFD SIMULATION

The unsteady CFD simulation of TWTAPM was carried out using commercial CFD code Ansys Fluent. The computational domain of the system was modeled and meshed using Gambit 2.3.16. The 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 50 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 (which is provided by the user) 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 turbulence model selected was k-ε model since it is valid for wide range of flows. The discretization for all flow variables is chosen to be of second order for increased accuracy. Discretization of Pressure was done with the PRESTO! Scheme because it has increased accuracy for the flow in porous media. The simulation has been carried out at different working fluids for argon, helium and the nitrogen

VI. RESULTS AND DISCUSSIONS

In the following, we discuss the simulation results along with the experimental results for the TWTAPM discussed above.

A. Effect of regenerator porosity

A regenerator in a TWTAPM is a porous medium with a high heat capacity. The pores in the regenerator are much smaller than the thermal penetration depth and hence the thermal contact between gas and solid material is very good. Figure 3 shows the effect of regenerator porosity on frequency. It shows that the frequency is not much affected by the regenerator porosity. But the regenerator porosity has significant effect on pressure amplitude. The pressure amplitude increases up to a porosity of 0.73 and then decreases which is depicted in Figure 4.

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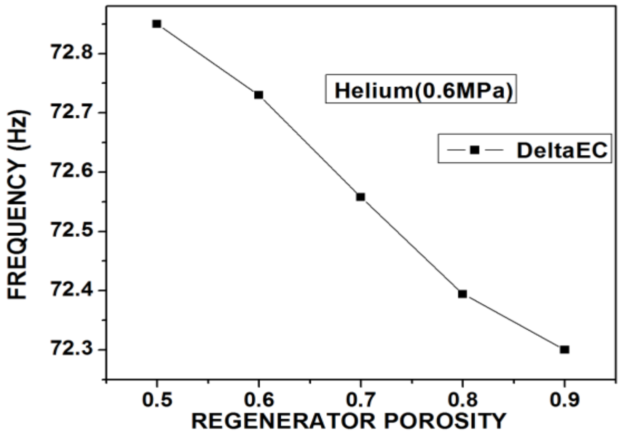

Figure 3 Variation of frequency with regenerator porosity

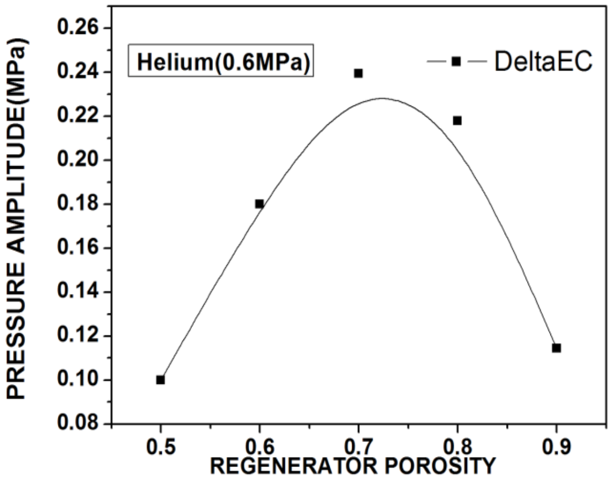

Figure 4 Variation of pressure amplitude with regenerator porosity

B. Effect of regenerator length

In order to find the optimum length of the regenerator for TWTAPM ,experimental and simulation was carried out with helium gas at 0.6MPa, regenerator porosity of 0.7 and by varying the regenerator length in the order 65mm, 85mm,105mm and 135mm. Figure 5 and Figure 6 shows the variation of frequency and pressure amplitude with regenerator length. The optimum regenerator length was found to be 105mm as it gives maximum pressure amplitude.

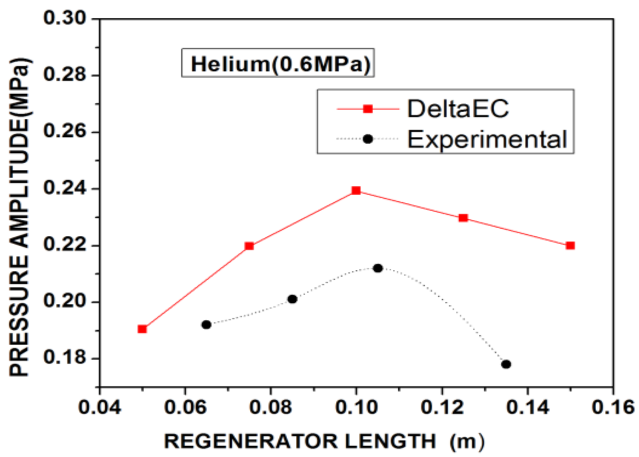

Figure 5 Variation of frequency with regenerator length

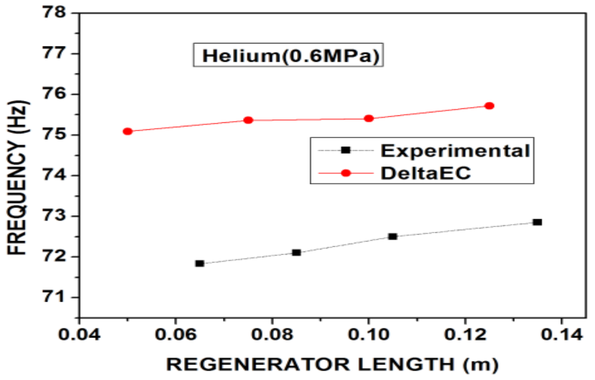

Figure 6 Variation of pressure amplitude with regenerator length

C. Effect of working fluid

The resonance frequency of the traveling wave system depends on the working fluid used. The resonance frequency of the system measured with different working fluid at different operating pressure and which are plotted. From the Figure 7, it is clear that the resonance frequency is nearly constant with variation of working pressure for a working fluid. The is due to the fact that the frequency of oscillation for traveling wave thermoacoustic prime mover is directly proportional to speed of sound in particular working gas..

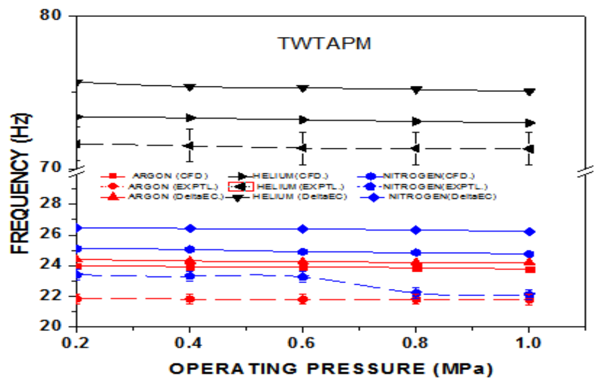

Figure 7 Experimental and simulated pressure amplitude as function operating pressure

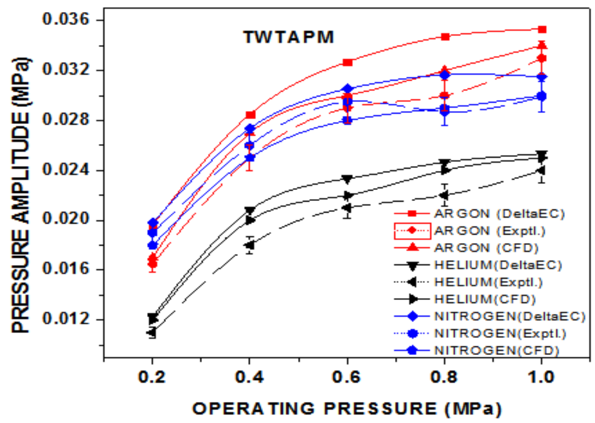

Figure 8 Experimental and simulated pressure amplitude as function operating pressure

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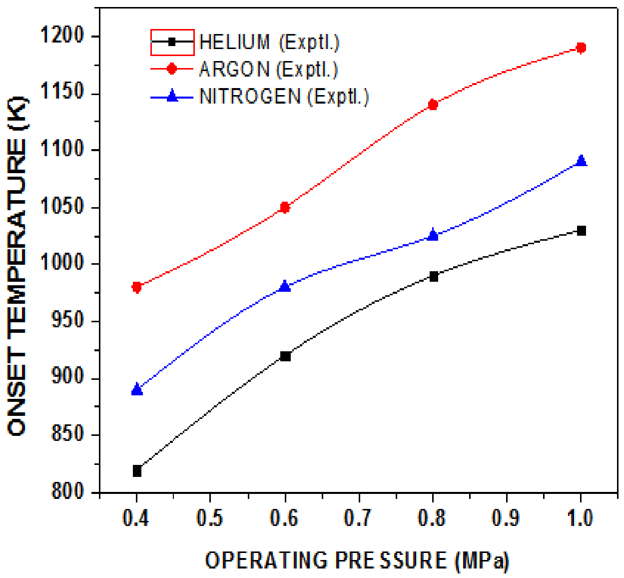

Figure 9 Experimental onset temperature vs system operating pressure

Increasing the operating pressure correspondingly increases the density of the working gas 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 helium shows highest frequency, since the density of gas within the constant volume varies according to the molecular weight. The molecular weight of helium is low and argon is high. Figure 8 shows experimental and simulated pressure amplitude as function operating pressure for Helium, Nitrogen And Argon.

The pressure amplitude which is directly proportional to the working pressure. According to linear thermoacoustics 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 that 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 gas and lowest for helium due to its lowest density .

From the Figure 9 it is clear that the offset temperature which is increases with the operating pressure it is because of the fact that if the pressure increase means that the gas density inside the system increases so more heat which required to operating the system it causing the onset temperature increases.

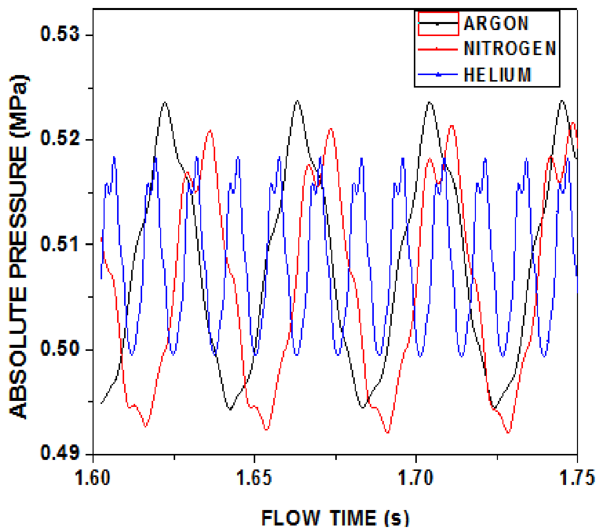

Figure 10 Stable Pressure oscillations in TWTAPM for helium, nitrogen and argon (CFD)

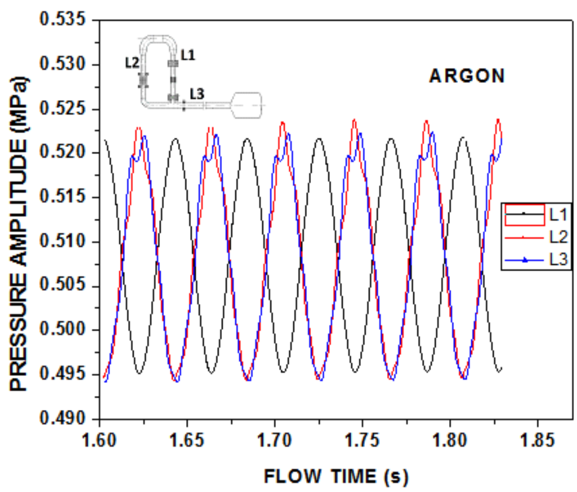

Figure 11 Pressure oscillations at locations L1, L2 and L3 in TWTAPM for Argon (CFD)

The pressure oscillations as predicted by CFD for different fluids are shown in Figure 10. Aomg the fluids, Argon shows the highest pressure amplitude at the lowest frequency of ~ 23 Hz at an average pressure of 0.51 MPa. Nitrogen indicates the medium pressure amplitude at a slightly increased frequency of ~ 24 Hz. On the other hand, helium shows the lowest pressure amplitude at the highest frequency of ~ 73Hz. The variation in frequency among the working fluids is due to the difference in their molecular weights, which modifies the sound velocity of the fluid.

Figure 11 shows the pressure waveforms as predicted by CFD at different locations (L1, L2, and L3) in the TWTAPM, with Argon as the working fluid at average pressure 0.51 MPa. The pressure transducer L1 is located above the cold end heat exchanger, L2 at the feed back tube and L3 at the mid of resonator tube. It is observed that the pressure waveforms in the loop have almost the same phases but their amplitudes vary depending on their locations.

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The system has its maximum pressure amplitude at the cold end next to the regenerator, which is perhaps the right location to extract the acoustic energy. The trends at different locations are reasonably in good agreement with the experimental values.

VII. CONCLUSION

The numerical and experimental studies on TWTAPM for different working fluids namely helium, argon and nitrogen at different average pressures. The CFD analysis indicates the following.

- With the increase in average pressure, the pressure amplitude increases with minor changes in frequency for all the working fluids investigated.
- Due to high molecular weight of argon shows lower frequency and for helium it is less and for nitrogen it is in between.
- The pressure waveforms in the traveling wave loop have almost the same phases but their amplitudes vary depending on their locations.
- The system has its maximum pressure amplitude at the cold end next to the regenerator, which is perhaps the right location to extract the acoustic energy.
- Increase in regenerator porosity increases the pressure amplitude and then decreases after an optimum value.
- Increase in regenerator length increases the pressure amplitude and then decreases after an optimum length with marginal variation in frequency.
- Onset temperature increases with increase in average pressure.
- CFD simulation predicts the presence of harmonics in the system.
- The pressure waveforms in the traveling wave loop and in the resonator are at different phases, but their amplitudes vary depending on their locations.

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