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Simulation studies on the performance of thermoacoustic prime movers and refrigerator

Mathew Skaria [a,*], K.K. Abdul Rasheed [a], K.A. Shafi [a], S. Kasthurirengan [b], Upendra Behera [b]

[a] *Department of Mechanical Engineering, TKM College of Engineering, Kollam, Kerala, India*
[b] *Centre for Cryogenic Technology, Indian Institute of Science, Bangalore, Karnataka, India*

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ABSTRACT

The prime movers and refrigerators based on thermoacoustics have gained considerable importance toward practical applications in view of the absence of moving components, reasonable efficiency, use of environmental friendly working fluids, etc. Devices such as twin Standing Wave ThermoAcoustic Prime Mover (SWTAPM), Traveling Wave ThermoAcoustic Prime Mover (TWTAPM) and thermoacoustically driven Standing Wave ThermoAcoustic Refrigerator (SWTAR) have been studied by researchers. The numerical modeling and simulation play a vital role in their development.

In our efforts to build the above thermoacoustic systems, we have carried out numerical analysis using the procedures of CFD on the above systems. The results of the analysis are compared with those of DeltaEC (freeware from LANL, USA) simulations and the experimental results wherever possible. For the CFD analysis commercial code Fluent 6.3.26 has been used along with the necessary boundary conditions for different working fluids at various average pressures. The results of simulation indicate that choice of the working fluid and the average pressure are critical to the performance of the above thermoacoustic devices. Also it is observed that the predictions through the CFD analysis are closer to the experimental results in most cases, compared to those of DeltaEC simulations.

1. Introduction

The energy conversion using thermoacoustic techniques has the advantages of constructional simplicity, absence of moving parts, reliable operation, long service life and no environmental pollution. It can use solar energy, waste heat and other low grade energies as a driving force, and finds applications in several fields such as power generation, refrigeration, waste heat utilization, and liquefaction of natural gas.

Thermoacoustic effect, which is the fundamental for the thermoacoustic energy conversion, refers to the interaction between the working fluid (a gas) and the solid medium, in the form of parallel plates or packed meshes, (similar to a regenerator) with appropriate porosity. This leads to the generation of acoustic oscillations in the presence of an appropriate temperature gradient across the above structure or reversely leads a time averaged heat flow when appropriate acoustic oscillations are propagated through the structure.

When the acoustic oscillations are generated by the application of temperature gradient, the system is referred as a Prime Mover (PM) or an Engine (E). On the other hand, when the acoustic oscillations are used to generate heat flux, this is referred to as a Refrigerator or a Heat Pump. Thermoacoustic devices may also be designated based on the type of acoustic wave passing the through the stack or regenerator as Standing Wave (SW) or Traveling Wave (TW) systems.

The standing wave thermoacoustic system comprises of a stack placed between two heat exchangers (referred as thermoacoustic core) and coupled to a resonator tube. In this system, acoustic oscillations are generated by the application of an appropriate temperature gradient across the stack and they set up a standing wave in the resonator tube. This is known as single ended type, when a single thermoacoustic core is coupled to the resonator tube whose opposite end is closed or open. On the other hand, it is called twin type, when two thermoacoustic cores are symmetrically placed at either ends of the resonator. The characteristic feature of the standing wave system is that the phase difference between the pressure and velocity is approximately 90°. This is caused by the imperfect thermal contact between the gas and the channel walls of the stack.

The performance of standing wave TAPM has been extensively studied for the stack, resonance tube, heat exchangers for different working fluids both theoretically and experimentally [1–8]. The

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* Corresponding author. Tel./fax: +91 9447606748.
E-mail address: mathewskaria@gmail.com (M. Skaria).

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Nomenclature

f	resonance frequency (Hz)
a	acoustic velocity ($\mathrm{m\,s^{-1}}$)
L	resonator length (m)
R	molar gas constant ($\mathrm{J\,mol^{-1}\,K^{-1}}$)
M	molar mass (kg/mol)
T	gas temperature (K)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
C_p	isobaric specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
Pr	Prandtl number (dimensionless)
U	volume flow rate ($\mathrm{m^3\,s^{-1}}$)
t	time (s)
p	pressure (Pa)
ΔT	temperature difference across the stack (K)
Greek letters	
γ	specific heat ratio of the working fluid (dimensionless)
δ_v	viscous penetration depth (m)
δ_k	thermal penetration depth (m)
μ	dynamic viscosity (Pa s)
ρ	density ($\mathrm{kg\,m^{-3}}$)
ρ_m	mean density ($\mathrm{kg\,m^{-3}}$)
ω	angular frequency ($\mathrm{rad\,s^{-1}}$)

twin standing wave TAPM generates acoustic waves with higher pressure ratio and larger amplitude than those of single ended type and hence it serves as an efficient drive for the cryocoolers and refrigerators [9]. The performances of such systems are found to be greatly influenced by the operational, geometrical and fluid parameters [10–12].

Similar to standing wave thermoacoustic prime mover, the traveling wave thermoacoustic system consists of a thermoacoustic core mounted inside a closed loop. In this case, the acoustic oscillations generated by the application of an appropriate temperature gradient across the stack/regenerator travels within the looped tube, such that the pressure and velocity components of the acoustic wave are in phase. The latter is caused by the perfect heat transfer between the gas and the channels of the stack. The traveling wave system also incorporates a section of a standing wave component namely the resonator along with a buffer, as discussed below.

Ceperley [13] showed that a traveling acoustic wave propagating through a regenerator undergoes a thermodynamic cycle similar to that of the Stirling cycle. Yazaki et al. [14] successfully constructed a pure TWTAPM which demonstrated better performance than the SWTAPM. However, due to the high acoustic velocities there were large viscous losses and this caused reduction in the efficiency. Backhaus and Swift [15] 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. A number of studies have focused on the optimization and selection of the stack/regenerators for traveling wave engines [16,17].

Refrigeration systems based on thermoacoustic effect also make use of thermoacoustic core, driven by acoustic waves generated either by a thermoacoustic engine or a loud speaker. This is referred to as Thermo Acoustic Refrigerator (TAR). Hofler et al. [18] invented a standing wave TAR in which the coupled oscillations of gas motion, temperature, and heat transfer in the sound wave are phased such that heat is absorbed at low temperature and rejected at high temperature. Extensive research has been carried out in the design and optimization for improving the efficiency of TARs. Garrett et al. [19] developed a thermoacoustic spacecraft cryocooler and it was used in the space shuttle ‘Discovery’. Tijani [20,27] designed and built a standing wave TAR and achieved a low temperature of ~ -65 °C. Swift [21] designed a large thermoacoustic engine to drive an orifice pulse tube refrigerator, which could liquefy natural gas.

The theories which have been applied for thermoacoustic systems are (a) oscillating flow theory [24], (b) fluid network theory [25,26] and (c) low amplitude linear thermoacoustic theory [22]. The numerical studies of thermoacoustic systems are largely based on the works of Rott, Greg Swift and Steven Garrett. Rott's theory [22] is based on the low amplitude linearization of the Navier–Stokes, continuity, and energy equations, with the assumption that all the variables undergo sinusoidal oscillations. Swift [23] modified the equations of Rott and developed the low amplitude linear thermoacoustic theory from which acoustic power and velocity amplitude, etc. can be obtained. Also a free software known as DeltaEC is now available from LANL, USA for the simulation of thermoacoustic systems. The numerical analysis of the thermoacoustic systems may also be carried out using commercial CFD codes such as Fluent and CFX which solves the continuity, momentum and energy equations.

In this work, experimental studies on twin SWTAPM and SWTAR have been carried out. The numerical analysis and simulation studies using CFD and DeltaEC respectively have been carried out for the above systems as well as the TWTAPM, which is experimentally studied by Chen and Ju [34]. The results of experimental studies are compared with those of numerical analysis and simulation studies.

2. Details of thermoacoustic systems

The resonance frequency and the pressure amplitude of a thermoacoustic prime mover depend on the operational parameters and the working fluid used. The resonance frequency of the open ended thermoacoustic prime mover is given by

$$f = a/2L = \sqrt{\left(\frac{\gamma RT}{M}\right)}\bigg/2L \tag{1}$$

This indicates that the resonance frequency depends on the acoustic velocity a of the working fluid and the resonator length L. The buffer volume commonly used in a thermoacoustic engine leads to stabilized frequency and improves the overall system performance. Further, to work as a prime mover to drive a pulse tube cryocooler, the frequency of the thermoacoustic engine should be lower and this necessitates either longer resonator tube or the use of the working fluid with lower acoustic speed. An effective way to decrease the operating frequency of the thermoacoustic engine is by an optimal design of the buffer volume in the system.

The performance of thermoacoustic prime mover also depends on the Prandtl number (Pr) of the working fluid, which is defined as

$$Pr = \mu \cdot C_p/k = [\delta_v/\delta_k]^2 \tag{2}$$

where the viscous penetration depth, δ_v is defined as,

$$\delta_v = \sqrt{2\mu/\rho_m \cdot \omega} \tag{3}$$

and the thermal penetration depth, δ_k is defined as,

$$\delta_k = \sqrt{2k/\rho_m \cdot C_p \cdot \omega} \tag{4}$$