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Simulation of a Thermo-Acoustic Refrigerator

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Abstract: *Thermo-acoustics deals with the conversion of heat energy into sound energy. Cooling devices based on the thermo-acoustic principal pump heat using acoustic waves. The devices are simple, have no reciprocating parts and have no negative effects on the environment. On the contrary, vapor-compression systems are complex devices along with having detrimental effects on the environment.*

This paper describes the software analysis of a simple Thermo-acoustic Refrigerator (TAR). Two software were used for simulating the TAR; ANSYS Fluent and DeltaEC. ANSYS Fluent was used to predict the turbulent and oscillatory nature of the thermo-acoustic effect with the simulation running for 50 computing hours to reach a sizeable conclusion. DeltaEC was used to calculate the final achievable temperature gradient of the TAR for an input of around 18.75 Watts and it concluded that a 12 K temperature gradient was reachable.

Keywords: *Thermo-acoustic, refrigerator, temperature, gradient, frequency*.

1. Introduction

1.1. Description of Thermo-Acoustic Refrigeration

The current method of heat pumping relies on the popular vapour compression cycle. The cycle consists of a compressor which compresses a refrigerant, which is then allowed to cool in an external condenser. Once the refrigerant is in the state of saturated liquid, an expansion valve or a similar component throttles the liquid resulting in a pressure and a temperature drop. The cooled refrigerant is then passed through an evaporator where it absorbs heat from the surrounding and the cycle continues.

There are obvious flaws with this cycle, firstly the use of a compressor which is a mechanical moving element means continuous operation of such a system is not possible as shutdowns are required for periodic maintenance and compressor lubrication. Secondly the use of Chlorofluorocarbons (CFCs) as refrigerants has had a detrimental effect on the environment and the ozone layer in the case of minor and major leakages.

The disadvantages of the vapor compression devices means other possible systems of refrigeration and cooling have to be investigated. Although none of these other systems are currently as versatile as vapor compression devices, some of these hold a high possibility of replacing the pollution causing vapor compression ones. Thermo-acoustic Refrigeration is one technique that involves the generation of a refrigeration effect by pumping heat across a temperature gradient. Acoustic waves are introduced in a resonator, converting the mechanical acoustic energy into a temperature differential. Thermo-acoustics is a science that is concerned with the interactions between heat (thermal) and pressure oscillations in gases (acoustics).

Thermo-acoustic refrigeration is a relatively new technology offering a number of benefits: Thermo-acoustic refrigerators have no moving parts, compared to conventional refrigeration systems which use reciprocating and other type of compressors. Hence these types of refrigerators can work for years continuously, without any need for dynamic sealing or lubrication problems. The working fluid used in thermo-acoustic refrigerators are noble gases such as argon, neon, krypton, binary composition of these gases or even air, though air reduces the refrigerator's efficiency. Since these working fluids are environmentally harmless, thermo-acoustic refrigerators provide a clean alternative to their current CFC reliant counterparts.

1.2. Theory of Thermo-Acoustics

In a thermo-acoustic refrigerator (TAR), acoustic waves go through displacement oscillations, and temperature oscillations in association with the pressure variation. An easy way to grasp the process is by picturing a tube closed at one end with a moving piston at the other end as shown in Fig. 1. The gas oscillates with the oscillations of the piston, producing regions of compressions and rarefactions within the tube. To produce the thermo-acoustic effect these oscillations should take place near the solid boundary of the resonator tube, so that heat is transferred between the oscillating gas and the solid boundary. To aid this heat transfer a spiral stack with a calculated stack separation is placed in the resonator to provide an increased surface area for the heat transfer. The movement of the piston is sinusoidal and the whole cycle can be broken into four thermodynamic processes:

1. Adiabatic Compression 2. Isobaric Heat Rejection

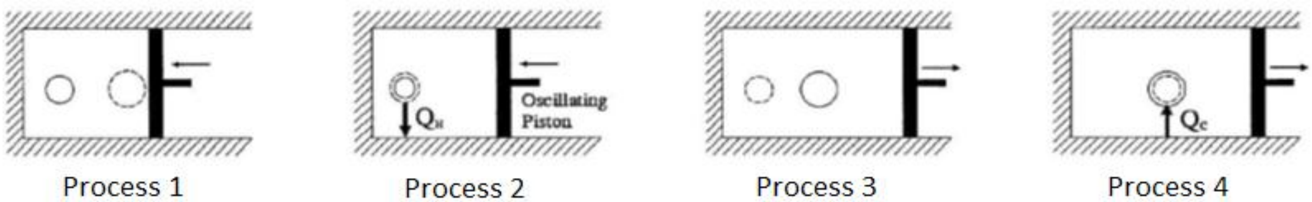

Fig. 1: Thermo-Acoustic Cycle [1]

3. Adiabatic Expansion 4. Isobaric Heat Absorption

• Process 1: Compression of the gas parcel as piston moves forward, thus heating up the gas parcel and displacing it.

• Process 2: Heat flows irreversibly from the displaced gas parcel to the wall due to temperature difference.

• Process 3: The piston moves back, resulting in the expansion of gas parcel. The gas parcel cools down and returns to its original position.

• Process 4: The cooled gas parcel absorbs heat from the wall as the wall is relatively at a higher temperature than the cooled gas parcel. The result is the cooling of the wall.

At the end of this cycle the gas parcel is at its initial state, both temperature and displacement wise and a net amount of heat is transferred from one section of the tube to the other section with the help of external oscillations. These oscillations are carried out by a compressor in a vapour compression cycle whereas in TARs, a speaker or a moving piston is used. If the system is allowed to reach a steady state, a temperature gradient appears along the wall. The resonator tube and the stack must have a high specific heat capacity and low thermal conductivity for the temperature gradient to persist. One end of the tube houses the acoustic driver while the other end must be closed to maintain a standing wave inside the tube.

Not all the gas molecules in the gas parcel take part in the heat exchange with the resonator/stack wall, in fact particles which are away from the wall don't have any thermal contact with the wall. The particles near the wall have good thermal contact with the wall but they are also responsible for viscous effects. The optimal place for a gas particle is such where the viscous effects are negligible but where thermal contact is strong enough for a considerable heat transfer. Thus the optimal distance depends on both the thermal and viscous penetration depths.

2. Research Methods

2.1. ANSYS Fluent

The Fluent module of ANSYS was used for simulating a section of the refrigerator to determine an overview of the expected results and predict the behavior of the thermo-acoustic effect. The working fluid was selected as Helium, as used by A. I. Abd El-Rahman and E. Abdel-Rahman in their numerical simulation. The rest of the design was based on a 2-dimensional cross section of the stack and resonating tube as a 3-dimensional design required a great deal of computing power. [2]

The reason for using Helium is associated with the fact that we were interested in the end result of the simulation which would predict the oscillatory behavior of temperature as particle velocity and pressure varies periodically. This oscillatory behavior stays the same regardless of the working fluid, however the simulation time is directly dependent on the effectiveness of the working fluid. Therefore Helium was selected as it is more effective than air and it saved us precious computing power.

The model is mostly focused on the stack geometry, the stack walls can be seen in Fig. 2 in the center on the top and bottom edge. The temperature gradient will develop across the length of the stack. This simplification of the geometry allows the results to be achieved in the minimum possible time while not compromising on the accuracy of the results.

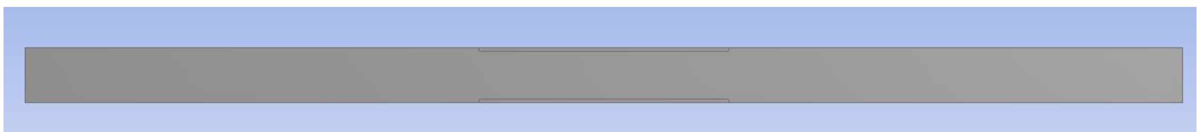

Fig. 2: ANSYS 2D Geometry

The meshing (Fig. 3) was done using medium smoothing settings with max face size of 1.5mm and a minimum edge length of 9.5e-2 mm. A total of 8781 nodes and 8469 elements were formed during meshing.

Using virtual topology (Fig. 4), the geometry was divided into different sections. Sections closer to the stack wall were given a finer mesh to capture the thermo-acoustic effect as heat exchange takes place near these stack walls.

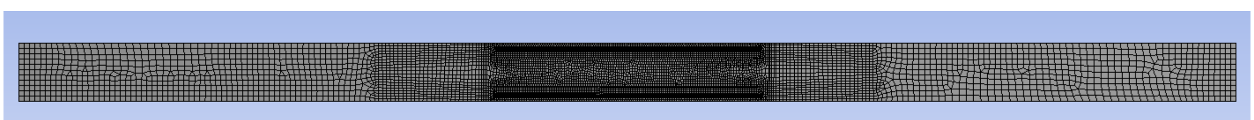

Fig. 3: ANSYS Mesh Geometry

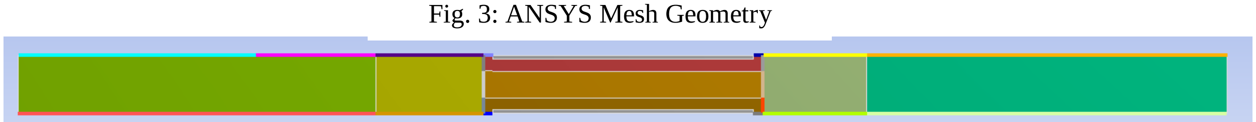

Fig. 4: ANSYS Mesh Virtual Topology

The red regions are the stack walls in the close-up view (Fig. 5).

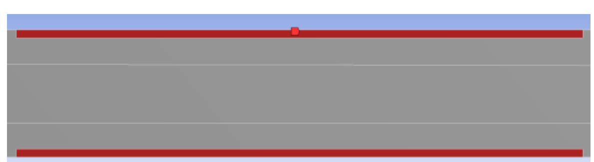

Fig. 5: ANSYS Mesh Stack Walls Close-up

The inlet wall (Wall A) and the outlet wall (Wall B) are defined (Fig. 6). The inlet wall serves as the acoustic driver's end and oscillates accordingly, the outlet wall reflects these oscillations to form a standing wave.

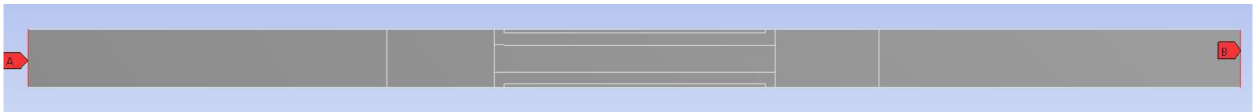

Fig. 6: ANSYS Mesh Inlet & Outlet Walls

Since these are moving boundaries, a dynamic mesh was setup and an ANSYS User Defined Function for their oscillating velocity was programmed using C language. The following equation was used:

$$u_{wall} = u_a \sin(kx) \cos(\omega t) \quad \text{Eq (1)}$$

Here, u_{wall} is the boundary/wall's oscillatory velocity at the time t,

k is the wave number,

x is the distance of the boundary from the acoustic driver's end,

ω is the angular frequency of the acoustic wave,

u_a is oscillating boundary's velocity amplitude and is dependent on acoustic pressure amplitude, the mean density and the speed of sound in the working fluid.

The resonant frequency of Helium was calculated to be 416.55 Hz, since the simulation is based on a quarter-wavelength design with a total resonator tube length of 60 cm. Fluent was initialized with parallel processing capability and was allowed up to 4 CPU cores and 1 GPU for parallel calculations. A pressure based solver with transient flow was used and the problem was modelled using K-epsilon turbulence model.

The calculation results were saved after every 100 iterations. The size of each time step was 20 micro seconds and a maximum of 30 iterations per time step were allowed.

2.2. DeltaEC

ANSYS Fluent required immense computing power and therefore could only be used to predict the transient oscillatory behavior of the temperature. The actual expected steady temperature gradient was simulated and predicted by Design Environment for Low-amplitude Thermo-acoustic Energy Conversion (DELTAEC) software.

DeltaEC simulates a given thermo-acoustic refrigerator under the defined conditions. It works by numerically integrating the one dimensional wave equation, momentum equation, continuity equation and the energy equation along the boundary conditions defined by the user. All oscillating variables are assumed to have a time dependence of Re($e^{i\omega t}$) [3].

A model on DeltaEC consists of multiple pre-defined modules attached to each other, each pre-defined module allows certain parameters to be set by the user. The numerical integration takes place from start to end of each module, thus solving the whole model. The following is the model of our thermo-acoustic refrigerator as viewed in DeltaEC:

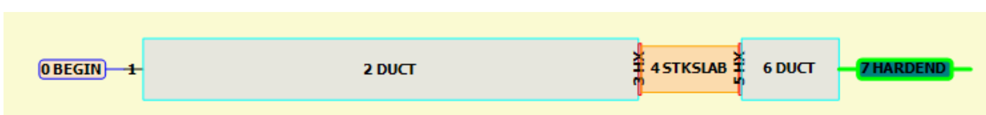

Fig. 7: Model of our TAR in DELTAEC

Calculations start from the Begin (0) module through the Speaker (1), Ducts (2), Heat Exchangers (3 and 5) and Stack (4) till the Hardend (7) module.

Each module has a list of parameters. Some of them can be set by the user while the others can be marked as guess variables which are to be calculated by the program through iterations.

For example, the Begin (Fig. 8) module defines the initial boundary conditions of the model, ranging from the mean pressure (P), beginning temperature (TBeg) and driving frequency (Freq) of the refrigerator. The volume flowrate (|U|) and its phase angle (Ph(U)) is marked as guess variables because they are dependent on the oscillation of the speaker diaphragm. Air is used as the working fluid since DeltaEC requires negligible computing time and the final simulated temperature gradient is dependent on the working fluid.

All modules follow a similar parameter structure. DeltaEC predicts the steady state temperature gradient and therefore cannot be used for transient behavior analysis, for which ANSYS Fluent was used. As a result, DeltaEC's computation time is negligible when compared to ANSYS Fluent's calculation time. A lower computation time means multiple models with different initial boundary conditions can be simulated to find the most effective one.

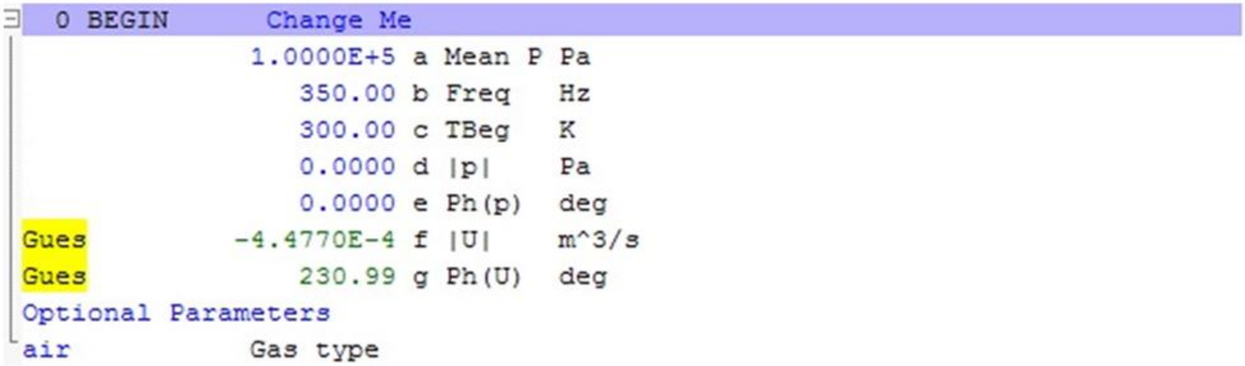

Fig. 8: DeltaEC Begin Module Setup

3. Result and Discussion

3.1. ANSYS Fluent

A total of 186000 time steps were performed and the total CPU time was 50 hours. A temperature gradient of 2.6 Kelvin developed across the stack as seen in the following figure:

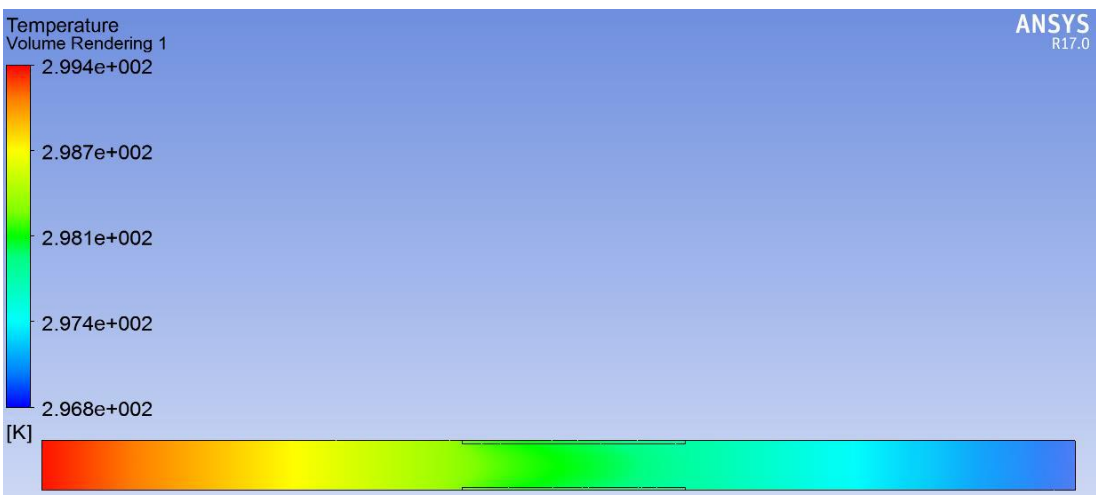

Fig. 8: ANSYS Simulation: Post 186000 time steps, 2.6 K temperature gradient appears

59 temperature readings were plotted across the time of simulation (Fig. 10). An important phenomena to notice is the transient oscillatory behavior of the temperature profile, as predicted by the thermo-acoustic theory.

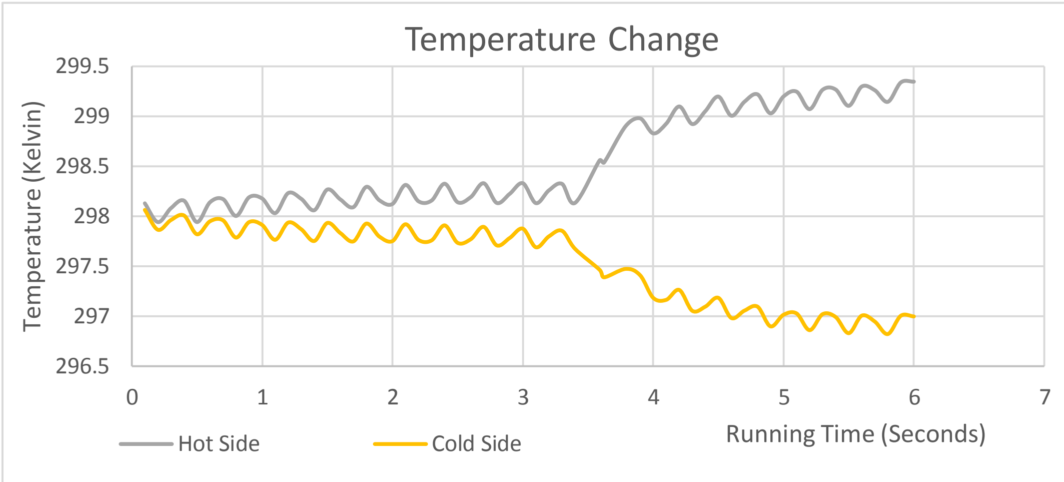

Fig. 10: ANSYS Simulation Temperature Graph

The simulation predicted that the temperature gradient of 2.6 K will develop during initial 6 seconds keeping in mind that there are no heat losses or gains from the surroundings.

The graph (Fig. 11) predicts the change in temperature over a prolonged period of simulation time, using a linear approximation.

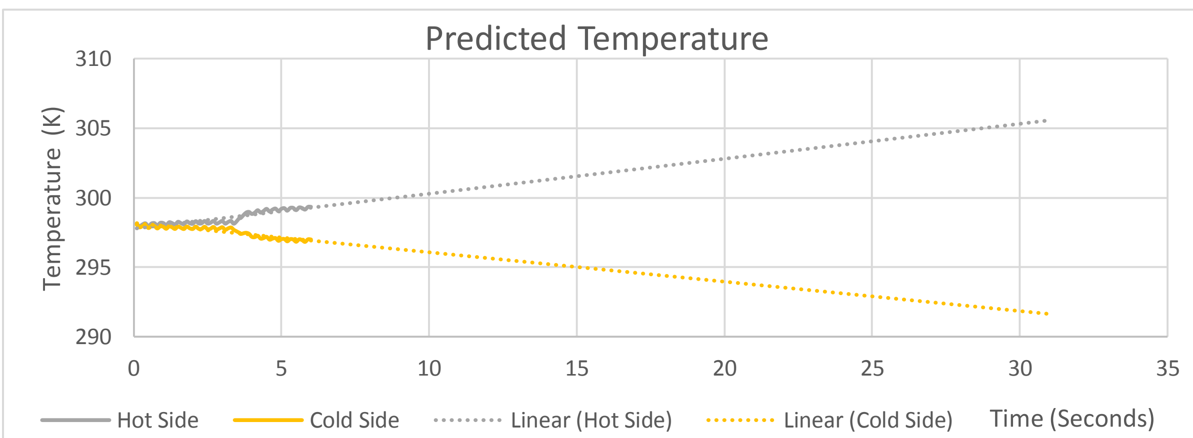

Fig. 11: ANSYS Simulation Predicted Temperature Graph

3.2. DeltaEC

DeltaEC runs on the principle of iterations hence the simulations were run multiple times to ensure convergence. Once the solution converged the following graph (Fig. 12) was displayed by DeltaEC.

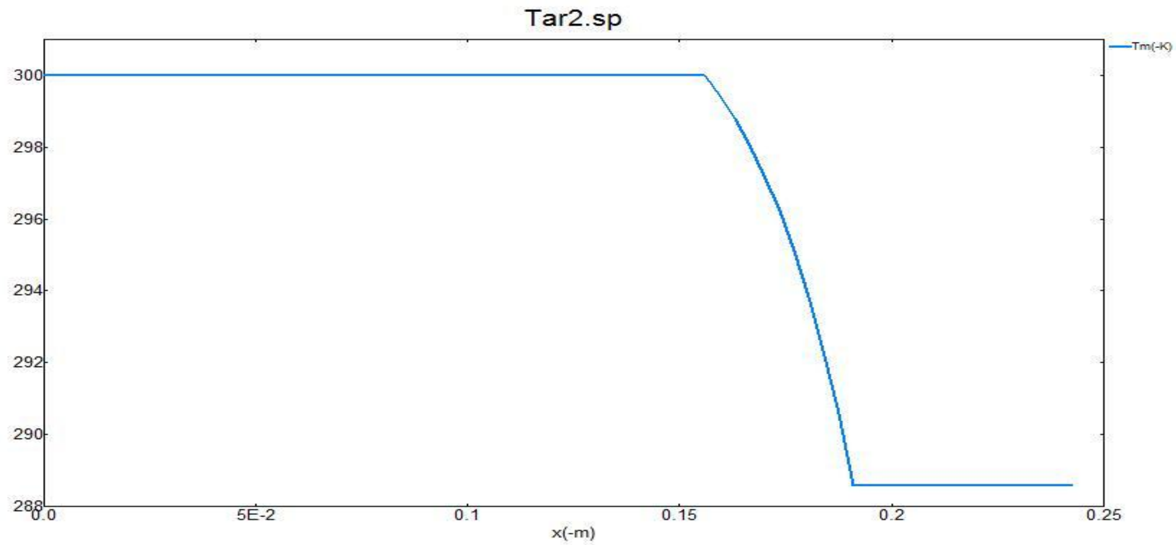

Fig. 12: DeltaEC Predicted Graph

The graph displays a plot of temperature against the distance, which is measured from the acoustic driver end. Around the stack a temperature drop of 12 K was predicted by the simulation.

4. Conclusion and Future Work

It is demonstrated through our simulation that a temperature gradient of 2.6 K can be achieved in initial 6 seconds of simulation run time. Graphical Solution of ANSYS results demonstrates the turbulent nature of the acoustic flow; the temperature gradient across the stack constantly fluctuates while increasing to a value corresponding to the input acoustic power. The DeltaEC simulation predicts a 12 K temperature gradient across the stack with an input power of 18.75 Watts.

The future work can include improving the ANSYS Fluent model by choosing K-omega turbulent model over K-epsilon model since K-omega is more accurate in computing internal flows, this would however require more computing power. The model can be simulated for a greater number of time steps requiring additional computing power. A working model based on this simulated data can be fabricated so that the actual results can be compared with the obtained analytical results.

5. References

[1] M. K. S. R. B. Masoud Akhavanbazaz, "The impact of gas blockage on the performance of a thermoacoustic refrigerator," *Experimental Thermal and Fluid Science,* vol. 32, no. 1, pp. 231-239, 2007.

[2] A. A. El-Rehman and E. A. Rehman, "Numerical simulation of a thermoacoustic couple," in *Acoustics 2012 Nantes Conference,* Nantes, 2012.

[3] Los Alamos National Laboratory, "DeltaEC," Los Alamos National Laboratory, [Online]. Available: http://www.lanl.gov/org/padste/adeps/materials-physics-applications/condensed-matter-magnet-science/thermoacoustics/computer-codes.php. [Accessed 25 October 2017].