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Analysis of Thermo-Acoustic Refrigeration System

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Abstract - *Thermoacoustic deals with the study of the inter relationship between heat and sound. A Thermoacoustic refrigerator is an arrangement that brings out the effect of cooling by means of using high intensity sound waves. The sound waves of high intensity are regarded to be pressure pulsations. These pressure pulsations come in proximity with the stack material that is situated inside a resonator tube. The sound waves travel inside the resonator tube leading to the formation of standing wave. The interaction between the original wave and the wave reflected back causes compression and rarefaction of the sound waves. This precipitates the heat transfer across both ends of the stack. By the usage of proper heat exchangers on either side of the stack, the lower temperature obtained can be used to attain the required refrigeration effect.*

***Key Words*: Thermoacoustic, Stack, Resonator tube, Thermoacoustic refrigeration, Moving coil speaker.**

1. INTRODUCTION

The most general exposition of thermoacoustics, as described by Rott, includes all effects in acoustics in which heat conduction and entropy deviations of the (gaseous) medium play a role. [1] In this paper, however, we will focus specifically on thermoacoustic devices exploiting the thermoacoustic concepts to produce useful refrigeration. The first qualitative explanation of acoustic effects was given in 1887 by Lord Rayleigh in his classical work "The Theory of Sound". He explains the production of acoustic oscillations as follows: "If heat be given to the air at the moment of maximum compression or taken from it at the moment of maximum rarefaction (expansion), the vibration is encouraged". [2]

The thermoacoustic effect can be understood by following a given parcel of fluid as it moves through the stack or regenerator. Fig. 1 displays the (idealized) cycles a typical fluid parcel goes through as it oscillates alongside the plate.[3] The fluid parcel follows a four-step cycle which depends on the kind of device. The four processes of cycle are mentioned as follow:

1) Isentropic compression
2) Isobaric heat rejection
3) Isentropic expansion
4) Isobaric heat absorption

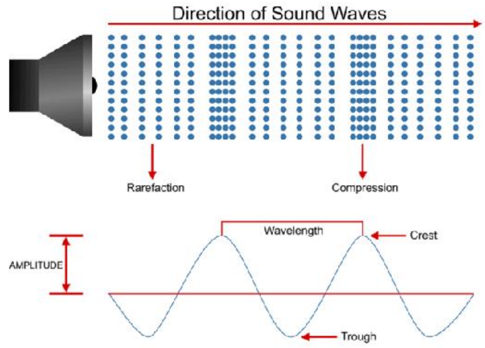


Fig -1: Phenomenon of Thermoacoustic

2. OBJECTIVE AND SCOPE

The present paper focuses on presenting a complete analysis of thermoacoustic refrigerators integrated with piezoelectric and moving coil elements. Design, modelling, construction and operation of prototypes of these thermoacoustic energy harvesters as well as the piezo-driven thermoacoustic refrigerators will be carried out. In terms of arithmetic modeling, this work also intends to present methods of combining the developed mathematical models with the commonly used thermoacoustic modelling software DeltaEC, while incorporating the attributes of the moving coil speaker in the resonators of thermoacoustic harvesters and the characteristics of speakers in thermoacoustic refrigerators. The performance of the prototypes of thermoacoustic refrigerators will be presented in the analysis segment of this work. Computations of key performance characteristics including but not limited to acoustic pressure and velocity waveforms, power flux and temperature distributions are carried out. Comparisons with numerical predictions are shown validating the findings of the developed theoretical models. Literature lacks a solid proposal of methods to enhance performance of refrigerators as cooling devices, specifically in terms of the energy altering efficiencies. The overall efficiency of the thermoacoustic energy is the result of the thermal to acoustic and acoustic to electric energy conversion efficiencies. In that sense, techniques adapted to enhance the given acoustic energy or the power output of the transducer should both reflect on a better overall efficiency in order to improve the performance of such a group of systems. Efforts attempted to achieve better acoustic power from the stack are mainly concerned with optimizing the stack. Parameters such as the material, porosity and spacing, and using different configuration of stack such as parallel plates, pin arrays and circular pores and/or changing the tube form and aspect ratio. This, however, results in a system that optimally performs at specific frequencies, exclusively regulated by the tube dimensions and the transducer parameters in order to satisfy the impedance matching condition. [4]

3. COMPONENTS AND PARAMETERS

3.1 COMPONENTS

Table -1: Components and their materials

Components	Materials
Acoustic Driver	Piezoelectric
Stack	Mylar, Kapton
Heat exchanger	Fluid Tubes: Copper Housing: Steel
Resonator Tube	Mild steel
Working gas	Air, Helium
Electronic Device (Amplifier)	-
Thermocouple	J type thermocouple

Table -2: Components and their specifications

Components	Specifications
Acoustic Driver	Frequency (50-500 Hz)
Stack	Thermal Conductivity (Mylar-0.15 W/m-K) Diameter: 50-100mm Length: 50-160mm
Heat exchanger	Length:100mm
Resonator Tube	Large dia.: 103mm Small dia.:56mm Resonator length: 700-1400mm
Working gas	Prandtl Number (20 C) = (Air=0.72, Helium=0.687)
Electronic Device (Amplifier)	Power output: 20 watts
Thermocouple	Thermocouple Grade: 0 to 150 C

3.2 PARAMETERS

Table -3: Thermo physical properties of Helium [5]

Parameters (Helium)	Specification
Speed of sound in gas	1013 m/s
Gas specific heat	5193 J/KgK
Gas thermal diffusivity	$13.2*10^{-5}$ m²/s
Gas thermal conductivity	0.155 W/mK
Gas density	0.8845 Kg/m³
Ratio of specific heats	1.67
Drive ratio	0.02

4. DESIGN

4.1 DESIGN STRATERGY

The goal in the design of a thermoacoustic refrigerator is to cover the requisites of a given cooling power QC and a given low temperature TC. These requirements are added to the operational variables. The low temperature TC is shown indirectly in the form of Temperature gradient ΔTm. The given table-4 shows the operational variables and working gas properties that are essential to approximate the design of thermoacoustic refrigerator. [6]

Table -4: Operating and working gas variables

Operational Variables	Working gas properties
Operational frequency f	Dynamic viscosity μ
Average pressure P_M	Thermal conductivity K
Dynamic pressure amplitude P_0	Sound velocity a
Mean temperature T_M	Ratio of isobaric to isochoric specific heat ɣ
Temperature gradient ΔT_M	Specific heat C_P
Mach Number M	Gas density ρ
Drive Ratio D	Prandtl number σ

Cooling power Q_C	

4.2 ASSUMPTION

1. The thermal conduction (i.e., heat leak from cold side to heated side) along both the sides of stack and the gas trapped in the stack is neglected.
2. The stack is relatively short to the wavelength of the acoustic standing wave.
3. The difference of temperature across the stack is a small fraction of the mean temperature of the stack and gas.
4. The heat and work flow are steady state.
5. The boundary layer viscosity is assumed to be zero.
6. The resonator pressure remains almost constant inside it.[7]

4.3 DESIGN PROCEDURE

A total of 5 basic components are to be designed of which stack is the most important. It is the most critical component when it comes to the functioning of the thermo acoustic refrigerator, as well as it has a determining effect on the design and orientating of all remaining components. Initially, to begin with the design of the stack, first the values of all parameters are required to be obtained and finalized. Sometimes direct values of some parameters are not available. Values at particular temperatures are accurately available and using pertinent formulae, the values at operating temperatures can be calculated. The temperature difference ΔT_M is indicative of the range of temperatures within which the system is going to be functioning. Given the lowest temperature T_C on cold side and the highest T_H at hot end one can obtain the operating temperature range which is nothing but ΔT_M. [8]

4.4 FREQUENCY

As the power in the thermoacoustic device is a linear function of the acoustic resonance frequency, an obvious choice is thus a high resonance frequency. On the other hand, K is inversely proportional to the square root of the frequency which again implies the very small plate spacing of stack plates. Making a compromise between these two effects and the fact that the driver resonance has to be maintained to the resonator resonance for high efficiency of the driver, the frequency of 267Hz was chosen. [9]

4.5 STACK DESIGN

The stack was designed and normalization of parameters is carried out to aid simplification. The length and position of the stack can be normalized by 2. The thermal and viscous penetration depths can be normalized by the half spacing in the stack y_0. The cold temperature or the temperature difference can be normalized by T_M. Since thermal conductivity k and volume v are related by Prandtl number, this will further simplify the number of parameters. The acoustic power W and the cooling power Q_C can be normalized by the product of the mean pressure P_M, the sound velocity 'a' and the cross-sectional area of the stack,

$$B = \frac{y0}{1 + y0}$$

It is also used as a dimensionless parameter for the geometry of the stack. It is taken as 0.75. The thermal and viscous penetration depths are given by,

$$\delta k = \sqrt{\frac{k * 2}{\rho * m * Cp * \omega}}$$

$$\delta v = \sqrt{\frac{2 * \mu}{(\rho * m * \omega)}}$$

Where, k is the thermal conductivity, μ is the viscosity, ρ is the density, Cp is the isobaric specific heat of the gas, and ω is the angular frequency of the sound wave. These resultant normalized parameters are given an extra index n. [10]

4.4 APPROXIMATED PROTOTYPE [CAD MODEL]

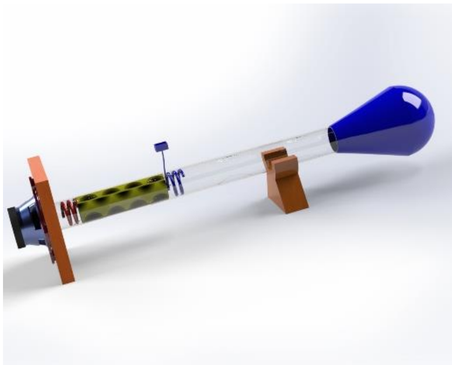


Fig -2: Prototype approximation

5. ANALYSIS AND RESULTS

5.1 THEORETICAL ANALYSIS

DeltaEC numerically integrate momentum, continuity and energy equation. We iterated few geometric and thermo physical parameter that affected thermo acoustic in DeltaEC software which are as follows:
Various parameters that are required for input in DeltaEC are:

- **Mean P:** It indicates the charging pressure inside the resonating tube.
- **Frequency:** It is the frequency of our acoustic source. It is measured in Hertz.
- **T_{Beg}:** T_{Beg} is short form for Temperature at beginning. Its value generally is equal to the value of surrounding.
- **|p|:** It is the dynamic pressure which is a function of amplitude of acoustic source.
- **Ph |p|:** It shows the phase of dynamic pressure.
- **|U|:** Flow rate in (m^3/s).
- **Ph |U|:** It shows the phase of flow rate. Flow rate and its phase both are kept as guesses in DeltaEC

s we cannot determine its value practically or theoretically.

Various geometric parameters which go into determining the design of thermoacoustic refrigerator are:

L_1: Length of duct between acoustic driver and stack.

L_s: Length of stack.

L_3: Length of duct after stack.

L_c: Length of cold heat exchanger.

L_h: Length of hot heat exchanger.

A_1: Area of duct between acoustic driver and stack.

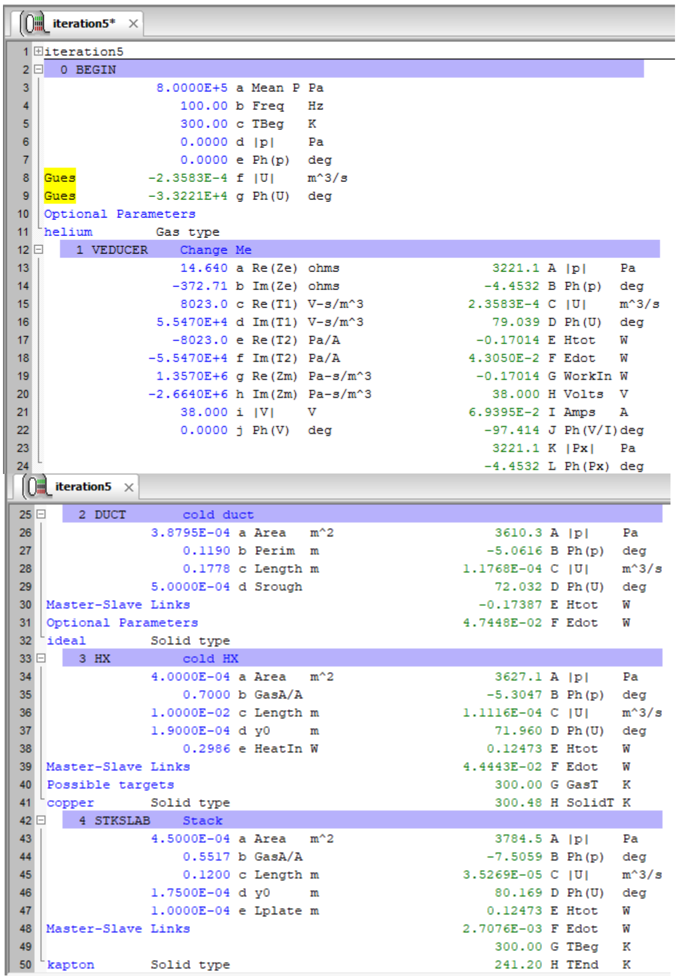
A_s: Area of stack.

A_3: Area of duct after stack.

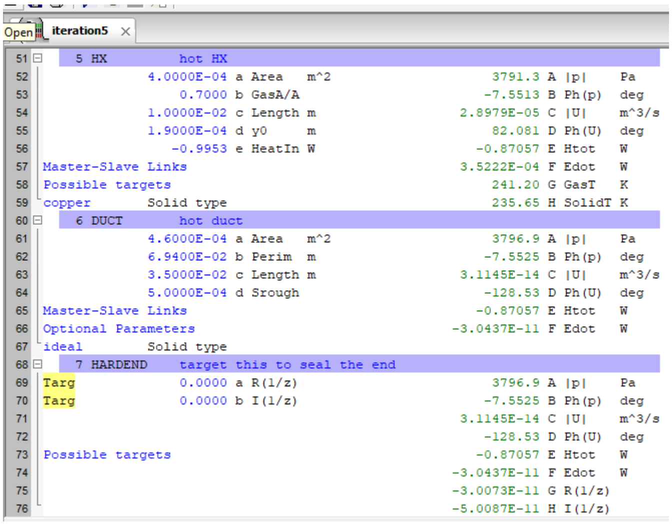
A_c: Area of cold heat exchanger.

A_h: Area of hot heat exchanger.

y_0: Distance between two layers of stack.



```
iteration5*
iteration5
  0 BEGIN
        8.0000E+5 a Mean P Pa
           100.00 b Freq   Hz
           300.00 c TBeg   K
           0.0000 d |p|    Pa
           0.0000 e Ph(p)  deg
Gues   -2.3583E-4 f |U|    m^3/s
Gues   -3.3221E+4 g Ph(U)  deg
Optional Parameters
helium          Gas type
   1 VEDUCER    Change Me
           14.640 a Re(Ze) ohms              3221.1 A |p|     Pa
          -372.71 b Im(Ze) ohms             -4.4532 B Ph(p)   deg
           8023.0 c Re(T1) V-s/m^3        2.3583E-4 C |U|     m^3/s
        5.5470E+4 d Im(T1) V-s/m^3           79.039 D Ph(U)   deg
          -8023.0 e Re(T2) Pa/A            -0.17014 E Htot    W
       -5.5470E+4 f Im(T2) Pa/A           4.3050E-2 F Edot    W
        1.3570E+6 g Re(Zm) Pa-s/m^3        -0.17014 G WorkIn  W
       -2.6640E+6 h Im(Zm) Pa-s/m^3          38.000 H Volts   V
           38.000 i |V|    V              6.9395E-2 I Amps    A
           0.0000 j Ph(V)  deg              -97.414 J Ph(V/I) deg
                                             3221.1 K |Px|    Pa
                                            -4.4532 L Ph(Px)  deg
iteration5
   2 DUCT       cold duct
       3.8795E-04 a Area   m^2               3610.3 A |p|     Pa
           0.1190 b Perim  m                -5.0616 B Ph(p)   deg
           0.1778 c Length m             1.1768E-04 C |U|     m^3/s
       5.0000E-04 d Srough                   72.032 D Ph(U)   deg
Master-Slave Links                         -0.17387 E Htot    W
Optional Parameters                      4.7448E-02 F Edot    W
ideal           Solid type
   3 HX         cold HX
       4.0000E-04 a Area   m^2               3627.1 A |p|     Pa
           0.7000 b GasA/A                  -5.3047 B Ph(p)   deg
       1.0000E-02 c Length m             1.1116E-04 C |U|     m^3/s
       1.9000E-04 d y0     m                 71.960 D Ph(U)   deg
           0.2986 e HeatIn W                0.12473 E Htot    W
Master-Slave Links                       4.4443E-02 F Edot    W
Possible targets                             300.00 G GasT    K
copper          Solid type                   300.48 H SolidT  K
   4 STKSLAB    Stack
       4.5000E-04 a Area   m^2               3784.5 A |p|     Pa
           0.5517 b GasA/A                  -7.5059 B Ph(p)   deg
           0.1200 c Length m             3.5269E-05 C |U|     m^3/s
       1.7500E-04 d y0     m                 80.169 D Ph(U)   deg
       1.0000E-04 e Lplate m                0.12473 E Htot    W
Master-Slave Links                       2.7076E-03 F Edot    W
                                             300.00 G TBeg    K
kapton          Solid type                   241.20 H TEnd    K
```



```
Open iteration5
   5 HX         hot HX
       4.0000E-04 a Area   m^2               3791.3 A |p|     Pa
           0.7000 b GasA/A                  -7.5513 B Ph(p)   deg
       1.0000E-02 c Length m             2.8979E-05 C |U|     m^3/s
       1.9000E-04 d y0     m                 82.081 D Ph(U)   deg
          -0.9953 e HeatIn W               -0.87057 E Htot    W
Master-Slave Links                       3.5222E-04 F Edot    W
Possible targets                             241.20 G GasT    K
copper          Solid type                   235.65 H SolidT  K
   6 DUCT       hot duct
       4.6000E-04 a Area   m^2               3796.9 A |p|     Pa
       6.9400E-02 b Perim  m                -7.5525 B Ph(p)   deg
       3.5000E-02 c Length m             3.1145E-14 C |U|     m^3/s
       5.0000E-04 d Srough                  -128.53 D Ph(U)   deg
Master-Slave Links                         -0.87057 E Htot    W
Optional Parameters                     -3.0437E-11 F Edot    W
ideal           Solid type
   7 HARDEND    target this to seal the end
Targ               0.0000 a R(1/z)           3796.9 A |p|     Pa
Targ               0.0000 b I(1/z)          -7.5525 B Ph(p)   deg
                                         3.1145E-14 C |U|     m^3/s
                                            -128.53 D Ph(U)   deg
Possible targets                           -0.87057 E Htot    W
                                        -3.0437E-11 F Edot    W
                                        -3.0073E-11 G R(1/z)
                                        -5.0087E-11 H I(1/z)
```

Table -5: Geometrical and Thermophysical parameter

Input Parameters	Iteration 1	Iteration 2	Iteration 3
Mean P (Pa)	7 E+05	5E+05	8E+05
Frequency (Hz)	300	200	100
T_{Beg} (K)	300	300	300
Gas	Helium	Air	Helium
Stack material	Mylar	Kapton	Mylar
L_1 (m)	0.1778	0.1778	0.1778
L_s(m)	7E-02	3.5E-02	0.12
L_3 (m)	3.5E-02	3.5E-02	3.5E-02
L_c (m)	1E-03	1E-03	1E-02
L_h (m)	1E-03	1E-03	1E-02
A_1 (m^2)	3.8E-04	3.8E-04	3.8E-04
A_s (m^2)	4.5E-04	3.8E-04	4.5E-04
A_3 (m^2)	4.6E-04	3.8E-04	4.6E-04
A_c (m^2)	4E-04	4E-04	4E-04
A_h (m^2)	4E-04	4E-04	4E-04

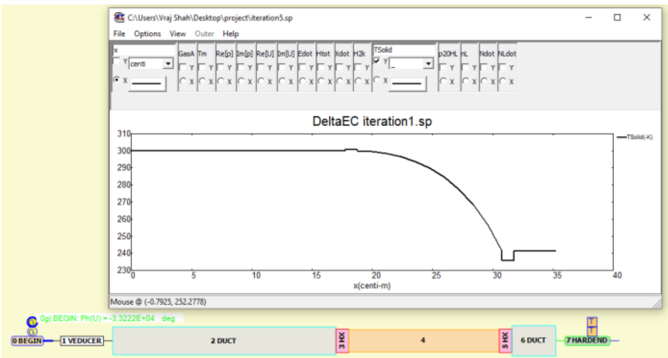


Fig -3: Result obtained from result 3 in form of temperature drop

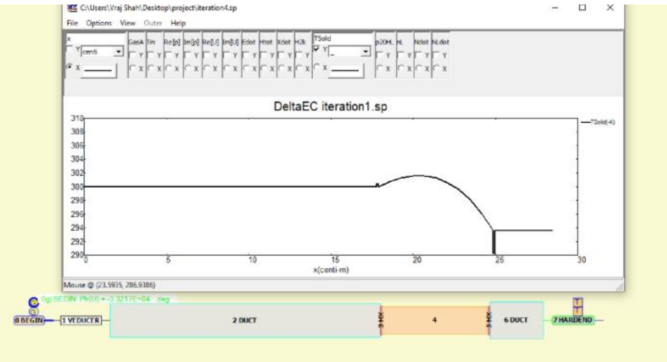


Fig -4: Result obtained from result 1 in form of temperature drop

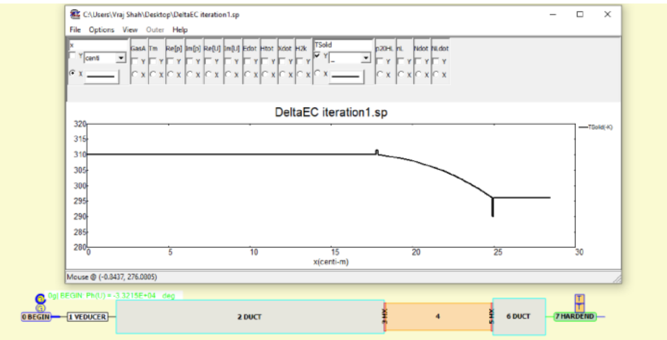


Fig -5: Result obtained from result 2 in form of temperature drop

5.2 RESULTS

The temperature drop across two ends of stack was obtained as the result of above codes and corresponding parameters.

- In the first iteration, a temperature drop upto 293K from 300 was obtained which gives the temperature difference around 7K.
- In the second iteration, a temperature drop upto 295K from 310K was obtained which gives the temperature difference around 15K.
- In the third iteration, a temperature drop upto 230K from 300K was obtained which gives the temperature difference around 70K.

6. CONCLUSION

Different optimization methods both numerical and experimental have employed to get lower temperature along with maximum temperature gradient across the stack region, least input power for producing a cooling effect and finally the coefficient of performance of the system. Several conclusions have drawn based upon past studies in the area of thermoacoustic refrigeration.
1. Thermal penetration depth and stack spacing are critical concerns for stack geometry. The final choice will be a compromise between the manufacturing suitability and thermal penetration depth.
2. Stack position from the driver end should be critically optimize to get desired output it should place near the driver end but not exactly at driver end, the results are severe when it is placed and exactly at driver end.
The novelty of this investigation in relation to similar ones is that it used materials that are relatively low cost and easily accessible. Such a solution can be generally recommended for the inexpensive thermoacoustic refrigerator designed for the demonstration of the basic physical principles of thermoacoustic phenomenon.

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