Experimental analysis of thermoacoustic refrigeration with combination of different gases and stack material

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Abstract - This project focuses on fundamental study and experimental analysis of thermoacoustic refrigerator. This research project considers the different variables that directly or indirectly affect the performance and reliability of thermoacoustic refrigeration. The variable parameter that is considered for analysis is working gases (helium, neon, argon, nitrogen), stack material and stack position. The efficiency of thermoacoustic refrigeration by finding the best combination of stack material, stack position and working gases for creating maximum temperature gradient across the stack.

***Key Words*: TAR, Resonator, Heat Exchanger, Stack & Loudspeaker**

1. INTRODUCTION

Thermo acoustic is the study of an elegant engineering field that involves both acoustics and thermodynamics - in other words, the study of fields that involve both acoustic waves and the conversion of one form of energy into another, such as heat into motion. Thermoacoustic thus describes energy conversion processes initiated by the interaction of the temperature oscillation accompanying by the pressure oscillation in a sound wave with solid boundaries. The significance of the term thermoacoustic, according to Nicholas Routt (who laid much of the theoretical foundation for the field) is fairly self-explanatory. As its name suggests, Thermoacoustic is a science that is concerned with the interactions between heat (thermo) and pressure oscillations in gases (acoustics)[1].This field can be broken into two subcategories. The first is the forward effect which is concerned with the production of pressure oscillations from heat. This result is primarily used to create engines that are widely referred to as thermoacoustic engines in the literature. The second subcategory or reverse effect is concerned with using acoustic waves to pump heat. This reverse effect is primarily used to create refrigerators known as thermoacoustic refrigerators which are the topic at hand.

Advantages of thermoacoustic refrigerator are that it is environmental friendliness, potentially high reliability due to simple structure and minimum number of moving parts, and realistic efficiency. These characteristics could lead to low manufacturing and maintenance expenditure.

2. Working Principal of Thermoacoustic Refrigeration System

2.1 Theory of Thermoacoustics

The continuity equation expressed above as equation (2.1) is repeated once again as follows

$$\frac{\partial \rho}{\partial t} + \nabla(\rho V) = 0 \qquad (2.1)$$

This equation is a function of the density and the velocity of the fluid. These two variables are expressed in difficult notation using the assumptions from the previous section as follows [2]

$$\rho(x,y,z,t) = \rho_m(x) + \rho_1(x.y.z)e^{j\omega t} = \rho_m + \rho_1 \quad (2.2)$$

2.2 Thermoacoustic Work

Now, we will proceed to develop an expression for the time-averaged acoustic power dW used (or produced in the case of a prime mover) in a segment of length dx in the stack. This power is the difference between the average acoustic power at x+dx and x, [3]

$$dW = A_g[\langle p_1 u_1 \rangle_{x+dx} - \langle p_1 u_1 \rangle_x] \qquad (2.3)$$

Here over bar indicates time average, brackets h i indicate averaging in the y direction, and Ag is the cross-sectional area of the gas within the stack. Expanding $\langle p_1 u_1 \rangle_{x+dx}$ in a Taylor series and p being independent of y, Eq (2.3) can be written

$$dW = A_g[\frac{dp_1\langle u_1 \rangle}{dx} dx] \qquad (2.4)$$

The time average of the product of two complex quantities such as p1 and u1 is given by,

$$\overline{p_1\langle u_1 \rangle} = \frac{1}{2} R_e[p_1\langle u_1 \rangle_x] \qquad (2.5)$$

Where the star denotes complex conjugation and Re signifies the real part. Using Eq. (1.4) and intensifying the derivatives in Eq.(1.3) as,

$$dW = \frac{1}{2} A_g R_e [p_1 \frac{d\langle u_1 \rangle}{dx} + \langle u_1 \rangle \frac{d\langle p_1 \rangle}{dx}]dx \quad (2.6)$$

To calculate this expression, the derivatives $\frac{d\langle p_1 \rangle}{dx}$ *and* $\frac{d\langle u_1 \rangle}{dx}$ *are essential The expression for* $\frac{d\langle p_1 \rangle}{dx}$ is obtained as below,

$$\langle u_1 \rangle = \frac{j}{\rho m \omega} \frac{dp_1}{dx} (1 - f_v) \quad (2.7)$$

After substituting the values,

$$\frac{dW}{dx} = -\frac{1}{2} A_g \omega (\frac{\rho_m I_m(-f_v)}{|1-f_v|^2} |\langle u_1 \rangle|^2 + \frac{(\gamma-1) I_m(-f_k)}{\rho_m a^2 (a+\varepsilon_s)} |p_1|^2) + \frac{1}{2} A_g \omega (\frac{\beta}{\omega(1-\sigma)(1+\varepsilon_s)} \frac{dT_m}{dx} R_e (\frac{f_k - f_v}{(1-f_v)} p_1 \langle u_1 \rangle)))$$

2.3 Thermoacoustic Energy Flow

This assumption must be removed for the energy flow since there are no first order terms involved. The centre of this section will be on second order terms and all variables that are second order. It is easy to see that the energy flux or total power flux E is the following:

$$E = -K \nabla T + v\sigma' + (\rho h + \frac{1}{2} \rho |V|^2) V \quad (2.8)$$

The second order power flow across the cross sectional area of a duct can then be written down as below,

$$E_2 = \int (-K \frac{\overline{\nabla T}}{dx} + \overline{V\sigma'} + \overline{\rho h u}) dA \quad (2.9)$$

Rott's acoustic approximation can now be used to simplify this equation. since all the terms inside the integral are time averaged, the first order parts of all the variables are zero. Keeping this in mind and examining the first term which is because of thermal conduction, it is assumed that the second order part is much less than the first order part, allowing the following generalization

$$\int (k \frac{\overline{\nabla T}}{dx})_2 \, dA = (Ak + A_{solid} k_{solid}) \frac{dT_m}{dx} \quad (2.10)$$

2.4 Boundary layer and short-stack Approximations

The thermoacoustic expressions got in the previous section are complex to interpret. In this section we will use two assumptions, to simplify these expressions. First, we make use of the boundary-layer approximation: [y0>> δK, l >> δs] so that the hyperbolic tangents can be set equal to unity. Second, we make the short-stack approximation, Ls<<< λ; where the stack is considered to be short enough that the pressure and velocity in the stack does not vary appreciably.

Finally, we will consider standing-wave systems, which are more related to the experimental work in this thesis. The standing wave acoustic pressure in the stack, ps1, can be taken as real and is given by [4]

$$p_1 = p_1^s = p_0 \cos(kx) \quad (2.11)$$

And the mean gas velocity in x direction is, [4]

$$\langle u_1 \rangle = j(1 + \frac{i}{y_0}) \frac{p_0}{\rho_m a} \sin(kx) + j \langle u_1^s \rangle \quad (2.12)$$

*T*he superscript s refers to standing waves, p_0 is the pressure amplitude at the pressure antinodes of the standing wave and k is the wave number. The factor $(1 + \frac{i}{y_0})$ is used because of the continuity of the gas volumetric velocity at the boundary of the stack, which involve that the velocity inside the stack must be higher than that

$$(1 + \frac{i}{y_0})$$

Outside by the cross-sectional area ratio The Rott's function f in the boundary layer approximation is given by [5]

$$f = \frac{(1-j)\delta}{y_0} \quad (2.13)$$

Using these assumptions and Ag = Πy0, As = Π1; the approximate expressions for W2 And E2 are obtained [3]

$$W_2 = \frac{1}{4} \pi \delta_k L_s \frac{(\gamma-1)\omega (p_1^s)^2}{\rho_m a^2 (1+\varepsilon_s)} (\frac{\Gamma}{(1+\sqrt{\sigma})\Lambda} - 1) \frac{1}{4} \pi \delta_v L_s \frac{\omega \rho_m \langle u_1^s \rangle^2}{\Lambda}$$

(2.14)

$$W_2 = \frac{1}{4} \pi \delta_k \delta_k \frac{\beta T_m p_1^s \langle u_1^s \rangle}{(1+\sigma)\Lambda(1+\varepsilon_s)} [\Gamma \frac{1+\sqrt{\sigma}+\sigma' + \sigma\varepsilon_s}{(1+\sqrt{\sigma})\Lambda} - (1+\sqrt{\sigma} - \frac{\delta_v}{y_0})] - \pi [y_0 k + l k_s] \frac{dT_m}{dx}$$

(2.15)

Where,

$$\Lambda = 1 - \frac{\delta_v}{y_0} + \frac{\delta_v^2}{2 y_0^2} \quad (2.16)$$

Ls is stack length, π is total perimeter of the stack plate and (π δk Ls) is the volume of gas within concerning a thermal penetration depth from the plates.

3. Instrumentation Setup

3.1 Resonator

The resonator tube is the hollow component of the resonator system. It is placed between the reducer and the buffer volume. To ensure low thermal conductivity, high strength, and light weight, the resonator tube was fabricated out of a

Aluminum. The resonator tubes consist of a small diameter tube, reducers, stack holder and buffer volume

3.2 Large Diameter Tube or Stack Holder

The necessities for the stack holder are stiffness and low thermal conductivity. We decided to construct the holder out of the material Nylon. The Holder is shown in Fig.5.1 It has inner diameter of 38 mm, a wall thickness of 5 mm and a length of 85 mm. It has two flanges for links to the taper and hot heat exchanger flange. The holder is coupled to the flange of the hot heat exchanger via six M5 bolts. A rubber O-ring, mounted into the flange of the hot heat exchanger is used for sealing because this junction is at room temperature.

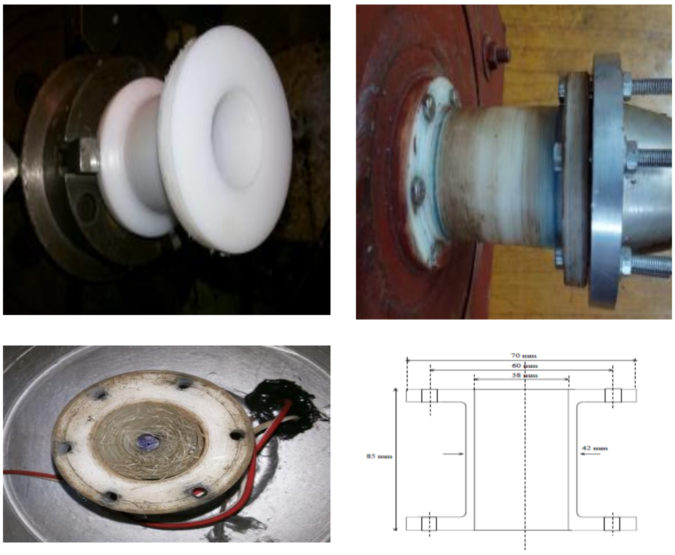

Fig. 3.1 Stack holder TAR

3.3 Buffer volume

The buffer volume is also made of aluminum. It has a volume of one liter, a wall thickness of 1 mm and a length of 27 cm. It is welded to the small diameter tube. A taper angle of 90 is used to reduce irreversibility. At the end of the cone pipe bowl was welded to make a buffer volume and on the other side small diameter tube was welded to the buffer volume as shown in fig.3.2.

Fig. 3.1 buffer Volume of TAR

3.4 Driver housing

Safety is must required to the drives, so one more square flange [300 mm*300 mm] with eight bolts [M10] is attached to the square flange of large diameter tube with circular buffer created with six inch inner diameter pipe as shown in fig.3.3 below.

Fig. 3.2 Driver housing TAR

2.4 Stack

The stack (Length- 85 mm) is manufactured from Mylar film (Thickness-75 micron), PVC (Thickness- 100 micron) and Lather (Thickness- 180 micron) and fishing lines (Material-Nylon, Thickness- acc. To thermal penetration depth) are used as spacers. By considering easiness in manufacturing we decide spiral geometry for the stack. The distance between two adjacent spacing lines is 5 mm throughout the cross section. This particular spacing ensured that the two layer of stack film do not touch other and the gas passage channels are uniform

Fig. 3.3 Stack Material & Design

3.5 Experimental Setup

Fig. 3.4 Experimental Setup TAR

4. Result & Discussion

4.1 N2 with PVC stack

Time (Hour)	Cold side(0C)	Hot side(0C)	ΔT
0.00	37.00	37.00	0.00
0.50	36.20	37.50	1.30
1.00	35.60	37.90	2.30
1.50	35.0	38.10	3.10
2.00	34.30	38.30	4
2.50	33.70	38.60	4.90
3.00	33.00	38.60	5.6
3.50	32.60	38.70	6.10
4.00	32.20	38.80	6.60

Table 4.1 Result of combination N2 and PVC

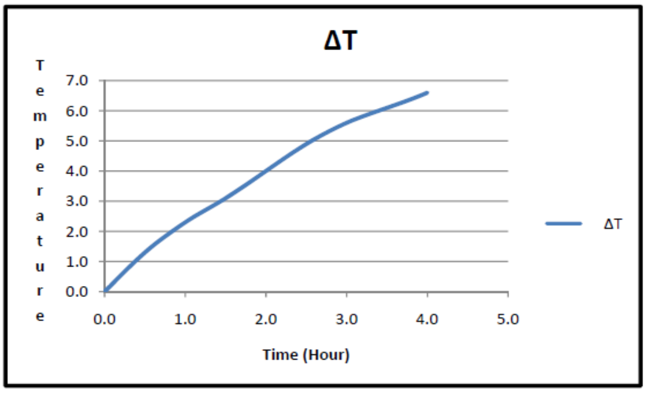

Fig 4.1 Time Vs Temperature profile N2 with PVC

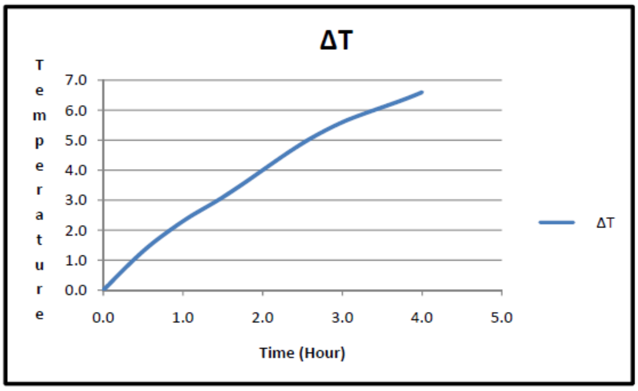

Fig 4.2 Temperature difference profile N2 with PVC

4.2 N2 with lather stack

Time (Hour)	Cold side(0C)	Hot side(0C)	ΔT
0.00	37.30	37.30	0.0
0.50	36.80	37.50	0.70
1.00	36.30	37.80	1.50
1.50	36.00	38.10	2.10
2.00	35.70	38.30	2.60
2.50	35.20	38.50	3.30
3.00	34.90	36.60	3.70
3.50	34.50	38.70	4.20
4.00	34.30	38.80	4.50

Table 4.2 Result of combination N2 and Lather

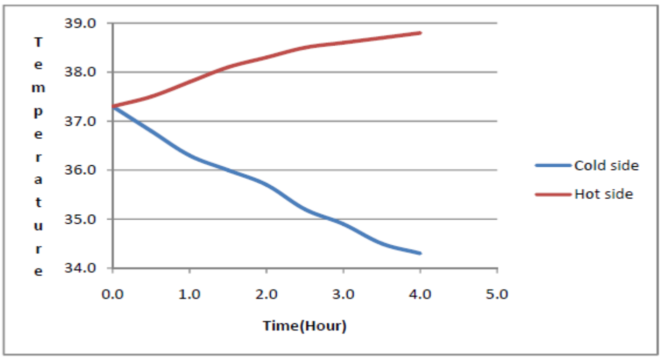

Fig 4.3 Time Vs Temperature Profile N2 with Lather

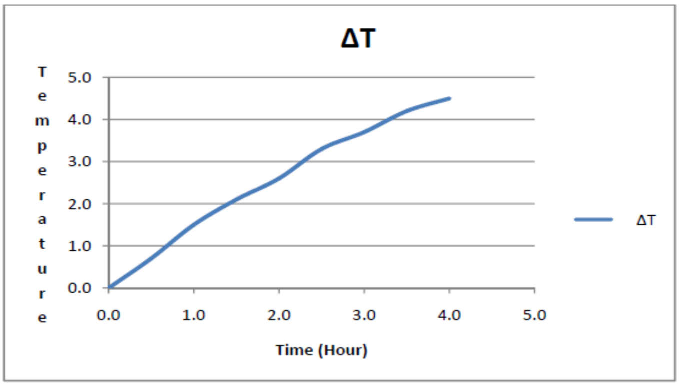

Fig 4.4 Temperature difference profile N2 with Lather

4.3 He with PVC stack

Time (Hour)	Cold side(0C)	Hot side(0C)	ΔT
0.00	36.00	36.00	0.0
0.50	35.80	36.50	0.700
1.00	35.00	36.90	1.90
1.50	34.50	37.00	2.50
2.00	33.90	37.10	3.20
2.50	33.00	37.30	4.30
3.00	32.50	37.30	4.80
3.50	32.30	37.50	5.20
4.00	32.20	37.50	5.30

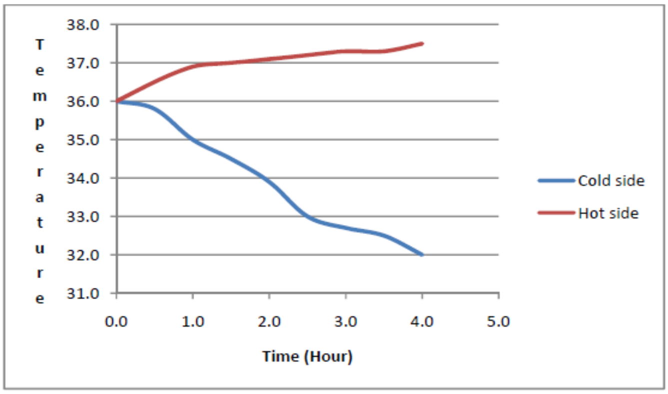

Fig 4.5 Time Vs Temperature Profile Helium with PVC

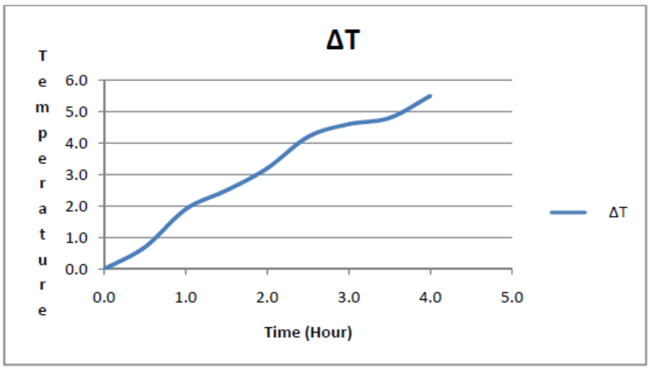

Fig 4.6 Temperature difference profile Helium with PVC

3.4 He with Lather stack

Time (Hour)	Cold side(0C)	Hot side(0C)	ΔT
0.00	35.00	35.00	0.0
0.50	34.50	35.20	0.700
1.00	34.00	35.30	1.30
1.50	33.80	35.50	1.70
2.00	33.30	35.60	2.30
2.50	33.10	35.60	2.50
3.00	32.80	36.70	3.90
3.50	32.50	36.80	4.00
4.00	32.40	36.90	4.50

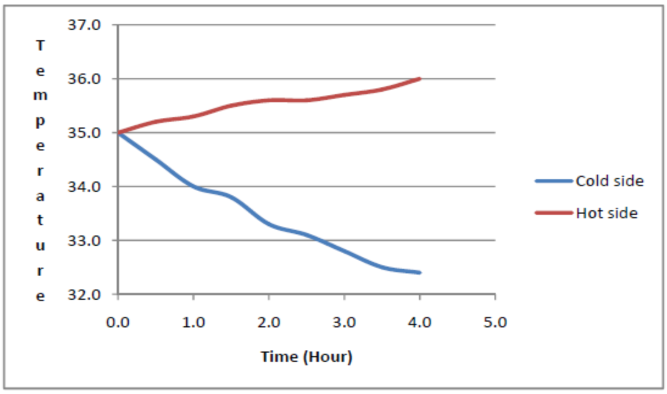

Fig 4.7 Time Vs Temperature Profile Helium with Lather

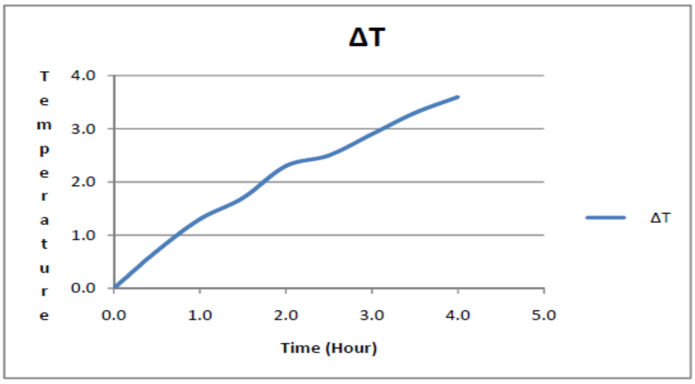

Fig 3.8 Temperature difference profile Helium with Lather

5. Performance analysis of TAR

The coefficient of performance of the device normalized by COPc = Tc/(TH –Tc) (the Carnot coefficient of performance) has been calculated as Here we compare the COP of N2 & He gas with stack material which produce the highest temperature gradient with others stack materials

Time (Hour)	Cold side(0C)	Hot side(0C)	ΔT
0.00	39.20	39.20	0.00
0.50	38.80	39.50	0.70
1.00	38.30	40.50	2.20

1.50	37.60	41.30	3.70
2.00	37.00	41.80	4.80
2.50	36.40	42.40	6.00
3.00	35.90	42.60	6.70
3.50	35.20	42.90	7.60
4.00	34.70	42.90	8.20

Table 5.1 Result of combination N2 and PVC

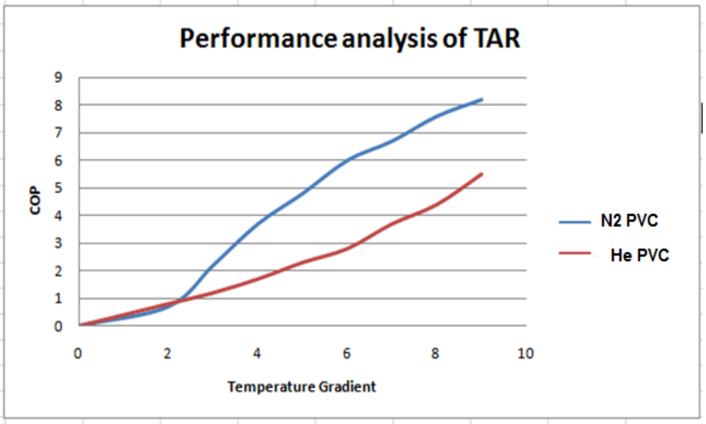

Fig 5.1 COP of TAR performed with N2 & He gas with PVC stack material

6. CONCLUSION

The proposed design help to analyse the cooling effect of various combinations of stack material and gases. By this research work, one can easily make the comparative study of the same and choose the best combination. By experiments, we conclude that quality of driver (Speaker) also had effect on performance of thermoacoustic refrigerator. From the result which was shown in Chapter 6 we can conclude that from all combinations of different gases and different stack materials, nitrogen as working gas and PVC stack gives highest temperature gradient and cooling effect. Proper heat transportation between the stack and heat exchanger and minimization of heat loss may enhance the performance of the thermoacoustic refrigerator.

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