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Study of a Thermoacoustic Refrigerator

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Abstract. *Thermoacoustic is a technology that uses high-amplitude sound waves in a pressurized gas generating hot and cold regions, so this device can be used as a heat pump or a refrigerator. This device has the advantage of no ozone-depleting or toxic coolant and few moving parts, as this refrigerator operates using sound waves to transport heat, then we can say this refrigerator is more economic and less poluent. This work compares numerical results with an experimental device. Numerical results were obtained using the specific package DeltaEc.*

Keywords: *Thermoacoustic, refrigerator, numerical simulation*

Symbols

μ	Viscosity
ρ_m	Density
γ	Ratio of specific heat
β	Volumetric expansion
k	Thermal conductivity
σ	Prandlt
T_m	Mean temperature
A	Cross sectional area
U_1	Oscillation velocity

1. INTRODUCTION

Thermoacoustic phenomenon has been noted for more than two centuries. Thermoacoustic Refrigerator uses wave acoustic propagation to compresses the fluid inside of the resonance tube. This refrigerator was constructed basically with a loudspeaker, a stack or regenerator, a heat and cold exchanger inside of the resonance tube, as shown in Fig. (1).

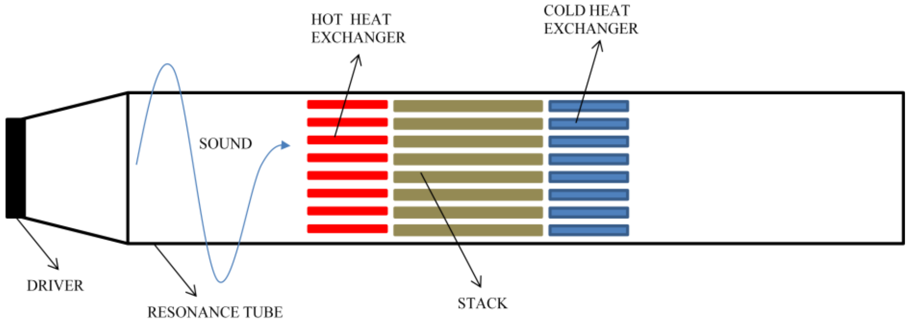


Figure 1. Thermoacoustic refrigerator

Inside the resonance tube filled with a gas (helium, air, and other kind of gas or a mix of them) which moves due to oscillation of the wave sound wave (pressure wave), that compress and expand this gas, generating two different zones of high and low pressure.

This pressure is amplified when the gas passes thru the stack core. So the thermal interaction between the oscillating gas and the surface of the stack generates an acoustic heat pumping. (Tijani et al, 2001). Hence the stack is the heart of the engine where the thermoacoustic cycle is generated (Tijani, 2003).

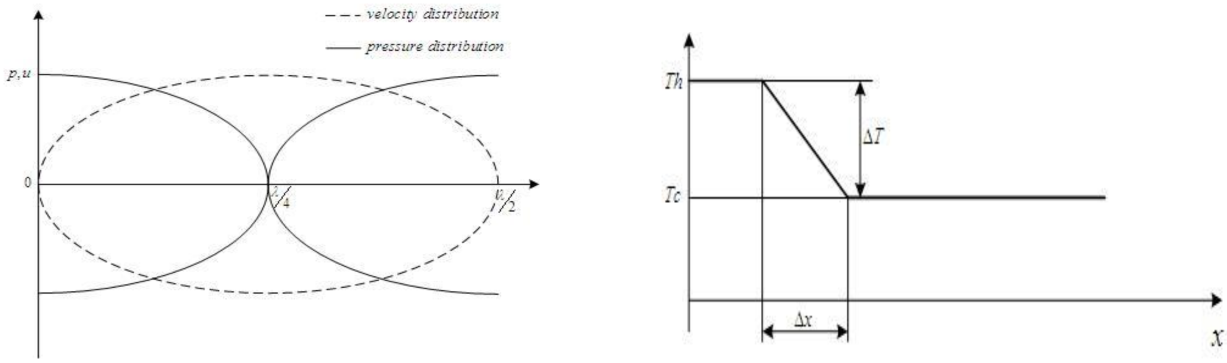
The Design and optimization of loudspeaker-driven thermoacoustic refrigerators is well covered by Tijani *et al.* in 2002 and also Wetzel and Herman in 1997. Further to these, the following comments are added for the design of low-cost thermoacoustic systems. (Zoontjens, 2005)

Qiu Tu (2003) studied the influences of the stacks position and the differents kind of the stacks in the thermal gradiente in the refrigerator. He showed the better configuration for the stacks was a plate shape, because this geometry is simpler to build experimentally and numerically, and the better position is the nearest pressure antinode.

This paper aims to study the temperature difference generated between the stack positions for different frequencies (250-350 hertz). For that the prototype was built to compare the results with the numerical model. The numerical analyze were performed with DeltaEC, Design Environment for Low-Amplitude Thermoacoustic Engines. The stack used in this paper, consisting of a number of parallel plates.

2. FORMULATION

According to Fig. (1) without the stack, an acoustic driver excites the working fluid in the resonate tube generating an acoustic standing wave. Considering the resonance tube length as λ/2, it can obtain the follow pressure and velocity profile Fig. (2a).



(a) (b)

Figure 2. (a) Pressure and velocity (b) Temperature distributions along the resonance tube (Herman, 1997).

The Fig. (2b) represents the temperature field when introduce the stack is introduced where Δx is the stack length, and ΔT is the temperature distribution inside the stack.

The principal parameters of a thermoacoustic refrigerator are the thermal penetration depth, δ_k, and viscous penetration depth, δ_v.

$$\delta_k = \sqrt{\frac{2k}{\rho c_p w}} \tag{1}$$

$$\delta_v = \sqrt{\frac{2\mu}{\rho_m w}} \tag{2}$$

The thermal penetration depth is the averaged thermal boundary layer between the stack's plate, and the viscous penetration depth describes the thickness of the layer of fluid around the stack plates.

Swift (1988) showed analytically the thermoacoustic effect, manipulating the equation of momentum, continuity, the energy using the thermoacoustic linear theory. So he obtained the "Rott's Equation", Eq. (3), where f_v, f_k *and* ε_s are the Rott's functions, *a*, is the sound velocity in the specific fluid, *w*, is the angular velocity.

$$\left[1+\frac{(\gamma-1)}{(1+\varepsilon_s)}f_k\right]p_1+\frac{a^2}{w^2}\rho_m\frac{d}{dx}\left[\frac{(1-f_v)}{\rho_m}\frac{dp_1}{dx}\right]+\frac{a^2}{w^2}\frac{(f_k-f_v)}{(\sigma-1)(1+\varepsilon_s)}\beta\frac{dT_m}{dx}\frac{dp_1}{dx}=0 \tag{3}$$

3. DELTAEC

DeltaEc software made in USA at Los Alamos and estimates the performance of thermoacoustic. This program considers a one-dimensional wave equation based on the usual low amplitude "acoustic" approximation.

This software divides the geometry in a sequence of segments, and solves them using 1-d wave equation for each segment (duct, stack thermoacoustic, and compilence). It calculates each segment considering the user defined variables as geometry and required enthalpy flow, considering the global variables as pressure and frequency

The boundary conditional used in DeltaEc solution are the continuity of temperature, pressure and volume velocity in each segment junctions. Following the three equations used by DeltaEc. The wave equation can be taken as the second-order Helmholtz Eq. (4) that can be written in two differentials equation for the pressure Eq. (5) and velocity and using the Root's wave Eq. (3), we can be written Eq. (6).

$$P_1 + \frac{a^2}{w^2} * \frac{\partial^2 P}{\partial x^2} = 0 \tag{4}$$

$$\frac{dp_1}{dx} = \frac{iw\rho_m}{A(1-f_v)} U_1 \tag{5}$$

$$\frac{dU_1}{dx} = -\frac{iwA}{\rho_m a^2}\left(1 + \frac{(\gamma-1)f_k}{1+\varepsilon_s}\right)p_1 + \frac{(f_k - f_v)}{(1-\sigma)+(1+\varepsilon_s)}\beta \frac{dT_m}{dx} U_1 \tag{6}$$

3.1. DeltaEc analysis

The first segment on DeltaEc is the "initial" segment, is set the following parameters:

- Mean pressure = $1*10^5$ Pa
- Temperature = 293 K
- Frequency = 250-350 Hz
- Velocity= 0
- Pressure Amplitude= 3000 Pa

The second and third segments were duct segment and have the following characteristics given in at the Tab. (1). The stack material was mylar, and the working fluid is air at atmosphere pressure.

	Refrigerator	Stack (plates)
Diameter	0.25 m	-
Length	0.23 m	$35*10^{-3}$ m
Spacing among the plates	-	$0,23*10^{-3}$ m
Plate's thickness	-	$0,30 *10^{-3}$ m
Position	-	0.17 m

Table 1. Dimension of refrigerator and stack.

In order to obtain better performance, the tube's dimension has length λ/4 for 370 Hz, and then we can use only a stack. In this paper were used different frequencies to study the behavior of the pressure and velocity, as shown the Fig. (3)

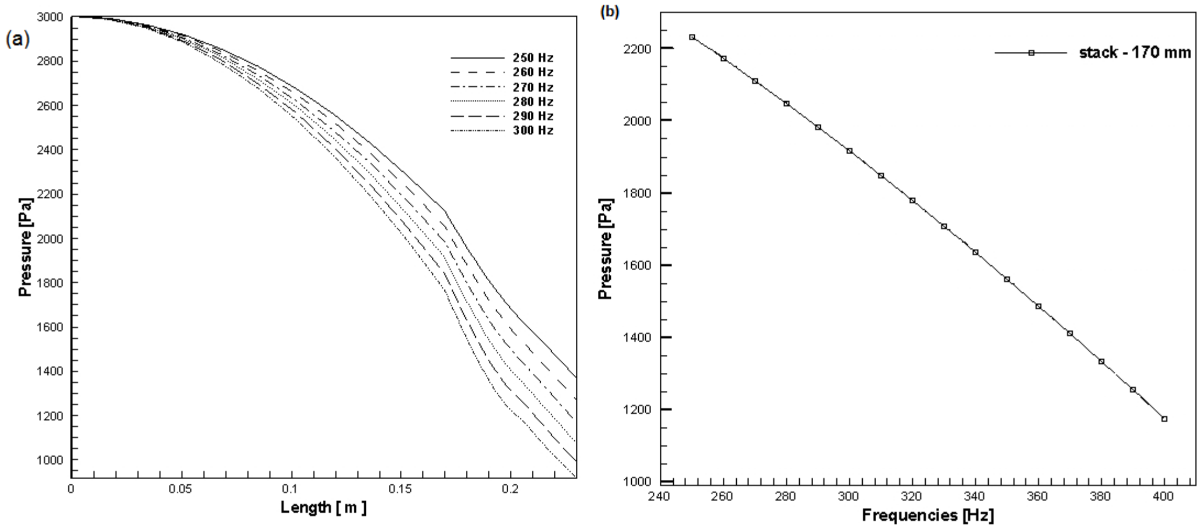


Figure 3. Pressure distributions [Pa] (a) for the length [m] the tube using different frequencies from 250 Hz to 300 Hz, and (b) the pressure for frequencies band (250 to 400 Hz) at 160 mm, position.

Fig. (3) represents the pressure distribution along the tube length, in steady state, using a band of frequency from 250 Hz to 350 Hz. We can note that the pressure decreases when the frequency increases

In Fig (3b) is used to show the pressure evaluate the excitation frequency influence at the position 0.17 m.

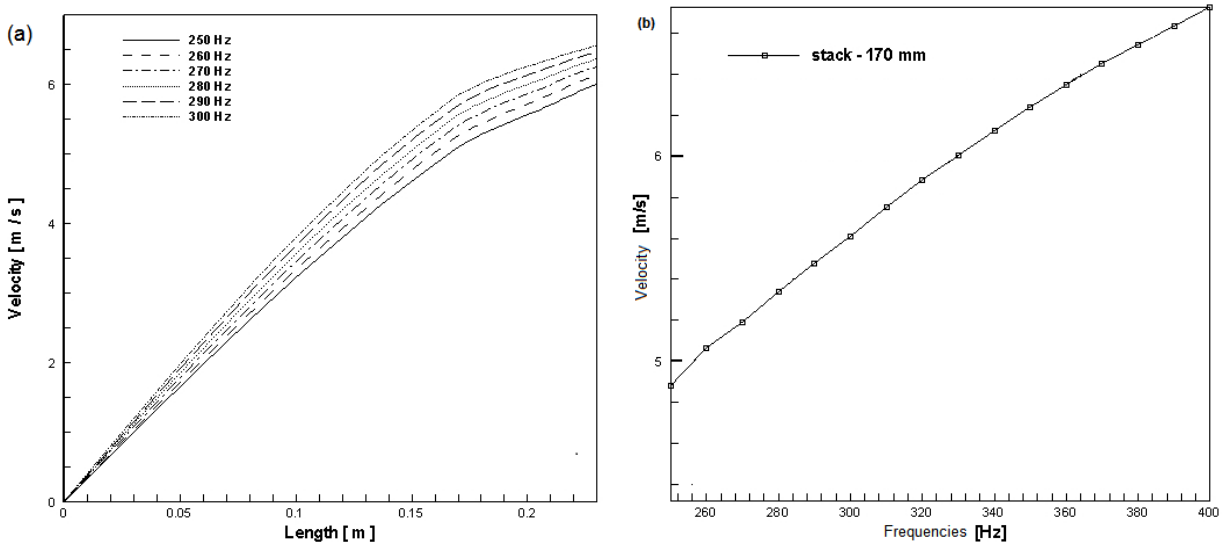


Figure 4. Velocity distributions [Pa] (a) for the length [m] the tube using different frequencies from 250 Hz to 300 Hz, and (b) the velocityxfr for frequencies band (250 to 400 Hz) at 160 mm, position.

Fig. (4) shows the velocity profile for a band of frequency from 250 Hz to 350 Hz. Due to the wave oscillation and the tube length it is possible to observe the velocity has a semi-parabolic behavior, accelerating near at the stacks place, because the transversal area reduction. This can be seen at the Fig (4a) and in Fig.(4b) is used to show the velocity evaluate the excitation frequency influence at the position 0.17 m.

4. EXPERIMENTAL ANALYSIS

The thermoacoustic device constructed for experimental analysis was made without concerning with the best efficiency. This project used a quarter standing wave length to build the resonator. This is consisting by a resonator an open-closed tube, a loudspeaker (driver) in the open side. A schematic drawing of the refrigerator is shown on the Fig. (5). It was measured the temperature in the hot and cold region.

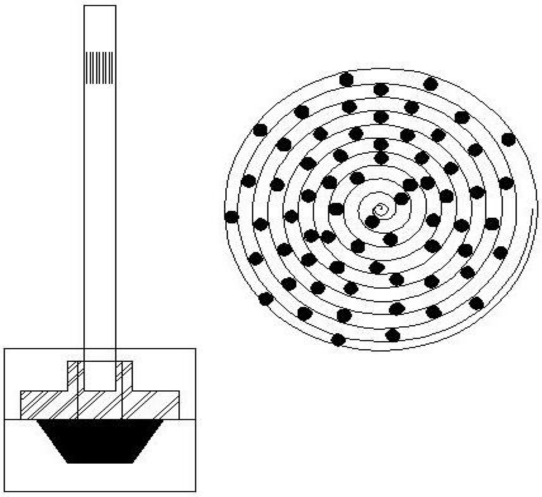


Figure 5 Schematic of the refrigerator and the stack.

The resonator is a glass tube with 0.23 m of length. This configuration defines a frequency of 370 Hz as for a quarter of wave. The loudspeaker is 0.08 m of diameter and a power of 50W. It is connected in an amplifier of 100 times. The tube was fixed on the loudspeaker using a flange, as showed Fig (5).

The stack consists of a large number of closely spaced surfaces aligned parallel to the length of the resonator tube. (A. Russell and Weibulla, 2002). This was built using the photographic paper and it is low conductivity ($\kappa \approx 0{,}18$ w/m.K at 300k) and its thickness is $0{,}2310^{-3}$ m, by winding likes a roll around a central spindle with the distance between the wall of the film the $0.30 *10^{-3}$ m. Thus we was used the nylon line between the surfaces, for propose of obtain the porous. The Fig (5) shows the refrigerator and porous schematic.

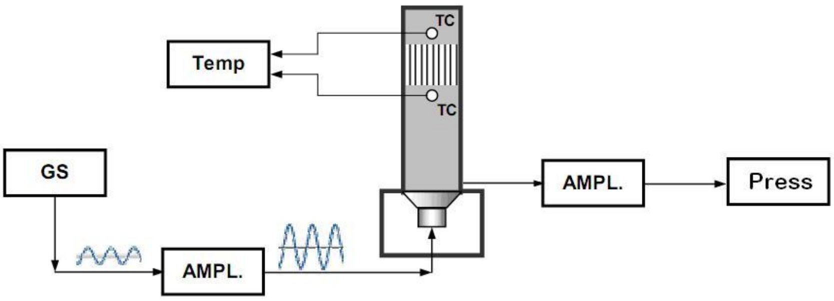


Figure 6. Schematic of experimental bench.

Temperature was obtained using two thermalcouples "T" connected in a 12- channel digital instrument, each one was located between the stack nearly one millimeter of the inlet and outlet, as shown the Fig. (6).

The pressure transducer (Danfoss MBs 3000) was used to determine which amplitude of the pressure. It was inserted in the bottom of resonator tube. Transducer sign is amplified and registered in an oscilloscope.

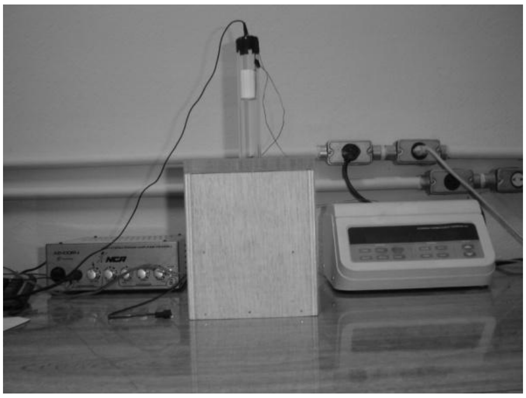


Figure 7. Image of experimental

Fig. (7) represents the experimental rig with the amplifier at the left, the digital temperature instrument at the right and the refrigerator in the center.

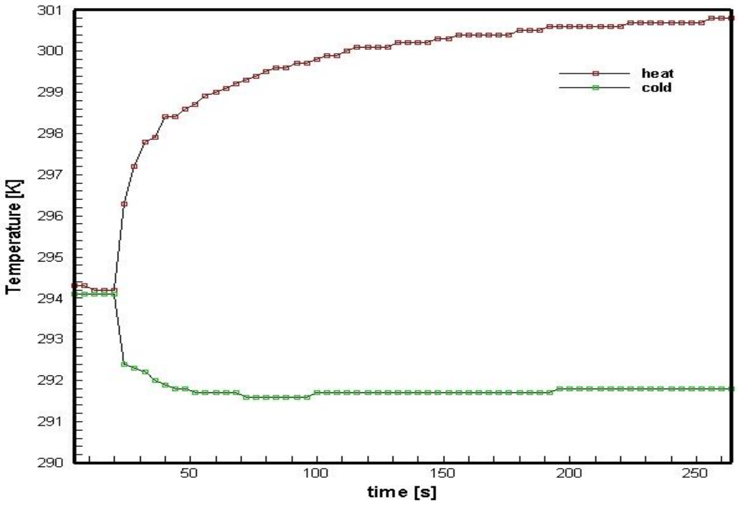


Figure 8. Behavior of experimental temperature to frequency 350 hertz by the time.

Fig.(8) shows the temperature behavior for the 350 Hz frequency with time. We can observe an elevated temperature gradient in a short time. The temperature measured by the thermocouple located in the cold region, tends to maintain constant after approximately 100 seconds. After this time the cold region begins to increase this temperature in function of the heat diffusion between the stack. This occurs because this device does not have heat exchanger at the hot and cold region.

The time used to obtain the hot and cold temperature was approximately to 250 s, this is due to the loudspeaker began to warming.

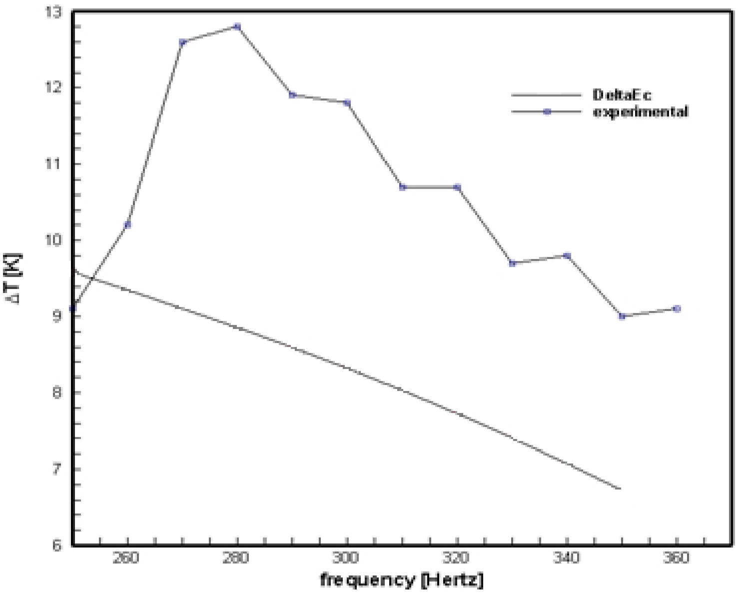


Figure 9. Temperature gradient [K] to any different frequency from 250 hertz to 350 hertz.

Fig (9) shows the temperature gradient for different frequencies. The graphic shows the both temperature gradient, experimental and numerical. The first was represented squares and was obtained in transient mode and numerical working at steady state mode.

At frequency 280 Hz the experimental shows the greater ΔT near 13 K. This is because the experimental device has a different stiffness of the numerical model, this occurs due to the supports used to fix the resonator to the loudspeaker and the pressure. After the maximum temperature gradient we can observe a temperature gradient decreasing with the frequency increasing, this occurs in function the stack is not positioned in its better position, where it was at the greater gradient pressure.

5. CONCLUSION

Software DeltaEc (Design Environment for Low-Amplitude Thermoacoustic Engines) shown, as a first analysis, very good performance, when compared with the experimental transient model and the experimental deviations can be explained in function of others variables.

The next steps are testing the other stack positions for the same frequency band. In order to improve this technology using the same software (DeltaEc), experimental analyzes and the full CFD solver.

6. ACKNOWLEDGEMENTS

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