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Experimental study of thermoacoustic cooling with parallel-plate stack in different distances

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Abstract. Thermo-acoustic is one of Non-Vapor compression cooling technologies also environmentally friendly technology developed rapidly to the present time due to its only use the sound wave to get the magnitude of cooling temperature with the oscillatory motion of the working gas pass through the *stack* inside a *resonator* is made in such manner, not use moving part such as the compressor. No lubrication system, low electricity consumption, and without the use of any chemical refrigerants so that the constructions, it will be more simplified and cheaper. The Stack is considered as the heart of the thermo-acoustic system which is the important heat transfer processes will be occur in this area. The variation of the shape, stack distances, kind of material stack applied on the system will be influenced the output of temperature as well. The writer will build a thermo-acoustic refrigerator with the parallel plate stack that is made from PVC Rigid sheets. This study will be done to see how the stack performance with temperature different aspect that would be achieved in the stack, the expectation on this experiment that the performance will have optimum result. The Writer also tried to conduct simulation with the DeltaEC's Software.

1. Introduction

The development of cooling technology over time has experienced many innovations that are oriented towards the achievement of cost aspects, simple forms and high efficiency. Currently conventional cooling systems that use vapor compression technology are still widely used in commercially as human needs for air conditioning are increasing, this vapor compression system uses compressors and chemicals refrigerant such as CFCs which are very detrimental to environment also the consumption of electrical energy to drive the compressor is consider still high. Nowadays there are many cooling systems being studied that use non-vapor compression HVAC technologies such as one of the institutions in America, the American Energy Department [6] makes a research target and ranks about the potential of HVAC technology options as describes in Figure 1 below. Thermoacoustic as a one of the choice of cooling method has many advantages if compared to conventional systems, including: no moving components, no use of chemical refrigerants and lubrication, simpler use of components, low electricity consumption and most importantly environmentally friendly [10][9]. Thermoacoustic can be a cooling tool with low cost and effective alternatives when compared to the current conventional system. Thermoacoustic is a field related to physical phenomena, where temperature differences can generate sound waves, and conversely sound waves can produce temperature differences [11], this cooling does not require a relatively expensive cooling fluid such as Freon or other chemical refrigerants but can use helium or free air as a sound wave propagation medium, this medium will produce differences in temperature when the acoustic waves is generated at certain frequencies.
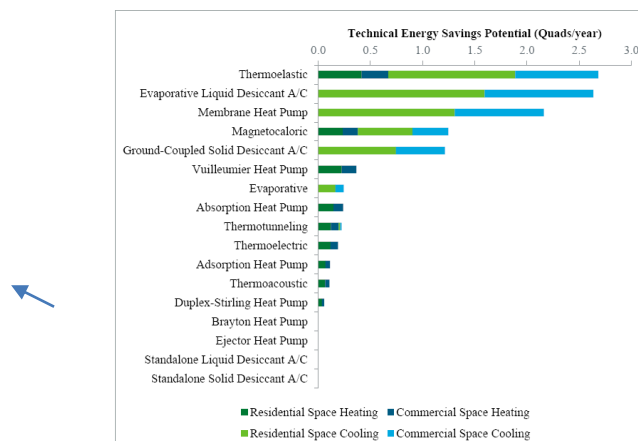
Figure 1. Technical Energy Saving Potensial [6]

A sound wave (acoustic) in a working fluid or gas is usually only seen as pressure and motion oscillations, actually the temperature oscillation is always the case. When the sound propagates in small canals, oscillating heat will also will flow to and from the canal walls [11]. The combination of all these oscillations will produce thermoacoustic phenomena or thermoacoustic effects, or in a easier understandable that the sound waves can cause temperature differences due to the air passing through small channels in the propagation. The thermoacoustic effect of the pressure and temperature changes due to sound waves on the resonator has been analyzed with reasearch by Tijani and his colleagues [18]. This phenomenon or effect can then be used as a refrigeration mechanism. The components used in thermo-acoustic refrigeration can be seen schematically in Figure 3 [22].
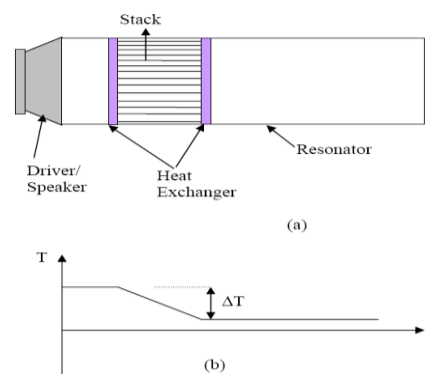
Figure 2. (a) Schematic of a thermoacoustic refrigerator, (b) Temperature variation across the resonance tube

The component consists of acoustic wave generators which usually use loudspeakers, resonators which are usually cylindrical (tube) and stack which usually use parallel plates. The thermoacoustic effect itself has been thoroughly examined for a long time with two very well-known tools, namely "Soundhauss tube" in 1850 and "Rijke tube" in 1858 [37] [41], however the theoretical explanation of the. Wheatley, Swift and others [28] [29][30] have developed a relationship between thermoacoustic components in general from the point of view of thermodynamics. The Thermoacoustic heat engine is further categorized into two types, namely "Standing wave engine" and the "Traveling-Wave engine". Currently the Traveling wave engine is better known as the Stirling engine [17] [5], while the discussion of thermoacoustic cooling engines generally refers to "Standing wave engine".

Many thermoacoustic studies have been carried out with various variations in geometry, major component modifications and engineering of the main parameters in an effort to improve the performance and efficiency of thermoacoustic machines. M.E.H Tijani [19] in his thesis and papers

has made a lot of research on thermoacoustic and has become a reference by other researchers in developing this thermoacoustic technology. The procedure and thermoacoustic refrigerator design optimization strategy using thermoacoustic linear theory has been introduced and described by M.E.H Tijani et al. [12], also the procedure for making and testing experimental thermoacoustic refrigerator performance has been carried out by Tijani et al. 65°C [13], optimization of stack design with parallel plate type has also been tested by looking for the optimal inter-plate distance (2yo) by Tijani, et al. and Stack Parallel plate form for cylindrical stack and resonator is the best form for thermoacoustic machine performance [14]. Further analysis of the improvement of thermoacoustic performance was developed by looking at the potential characteristics of the working fluid such as seeing the effect of the prandtl number on the thermoacoustic refrigerator as described in the paper Tijani, H. Zeeger and M.D. Waele [16] and concludes the COP machine will be high with a low prandtl value. Russell & Weibul [42] have been able to realize and operate a thermoacoustic cooling machine with a temperature difference between the hot tendon and cold tendon of 15°C within four minutes of the start of operation. Mathematic studies have also been analyzed by many mathematical equations like those conducted by PHM Wihelmus [25] as well as the general formulas outlined by Arnott et al. In his paper [1], Weismen & Diana [43] also outline many mathematical modeling in optimization of thermoacoustic components, making it easier for other researchers to determine design parameters.

In Indonesia, too many studies have been conducted, for example by Iksan Setiawan, et al. [11] who have successfully designed and made thermoacoustic devices as refrigerants and heaters simultaneously, Iksan setiawan [10] also made an experiment about the porosity effect of the stack. Anastasia et al. [4] have analyzed the effect of the frequency of operation and stack length experimentally using a porous stack from gambas material, which concluded that the optimal frequency is at 103Hz with the maximum temperature difference between the heat reservoir and the cold tendon of 4.7°C while the stack length optimal around 6 cm. Edy Hartulistiyoso and Muhamad Yulianto [9] also made research on the potential of Bamboo to be used as a resonator tube material. Analysis of the effect of hydraulic spacing from the stack was also carried out by Prastowo et al. [23] concluded that the greater the hydraulic track value, the temperature difference on onset tends to be smaller and the stack length also affects the difference in the temperature of the onset and the time of the sound. With the potentials and advantages of the thermoacoustic system when compared to the current conventional cooling technology system, it is deemed necessary for the advancement and development of cooling technology to conduct further studies and research on thermoacoustic systems, especially in the hope that this technology can be applied to rural technology. , application in the field of cooling of transportation equipment, cooling of electronic devices.

## 2. Basic Principle of Thermoacoustic

The word "Thermoacoustic" comes from a combination of 2 words, namely "Thermo" or heat, and "acoustic" or sound. Thermoacoustic is the interaction between temperature, density and variations in sound wave pressure. Thermoacoustic works based on the principle that sound waves will also cause wave pressure, while sound waves (acoustics) in a working fluid or gas are usually only viewed as pressure and motion oscillations, whereas temperature oscillations always occur. When the sound propagates in small canals, oscillating heat will also flow to and from the canal walls [11]. The combination of all these oscillations will produce thermoacoustic effects, or in a more understandable sense are sound waves that can cause temperature differences because of the air through small channels in the propagation, this principle is used in the thermacoustic refrigerator. This system rely on two main principles of thermodynamics.

First; the temperature of the fluid will rise if compressed and down when expanding on a fixed volume.

Second; when two substances or objects are attached directly, the heat will flow from substances/objects that are hotter to cooler objects.

There are 2 types of thermoacoustic devices namely thermoacoustic engine and thermoacoustic refrigerator. In the thermoacoustic engine heat is converted into sound wave energy and this energy is able to be used for work, while thermoacoustic refrigerator is the opposite of the process that occurs that uses sound waves to absorb low temperature heat and remove heat in high temperature media. A thermoacoustic device consists of a loud speaker, where the sound is directed to the resonator tube which has been filled with working gas for example air, helium or other gases, and a stack is made with a thin layer of plate where the thickness and distance between plates are determined, there is also a pore circular stack, the stack equipped with heat exchanger at the ends of the stack to utilize the cold temperature produced can then be used for various things. A simple illustration of the thermoacoustic system in a standing wave can be seen in Figure 2.

Stack (also called regenerator) is a place where a heat pump process consists of small canals in such a way that the plates is placed parallel to the resonator which is used for the purpose of producing a temperature gradient along the layers of the plates.
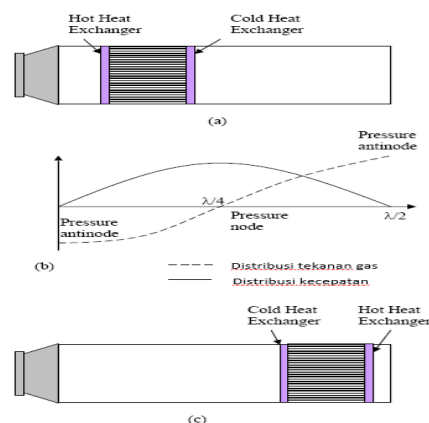
Figure 3. (a) Stack position for λ/4, (b) The Temperature & pressure distribution along the resonance tube, (c) Stack position for λ/2

3. Thermoacoustic Cooling Cycle & Heat Transfer Processes

As explained earlier that the stack can be said to be the heart of the thermoacoustic system because the heat transfer process occurs here, then if we take a small portion of the inter-plate channel image for our analysis from the example of the parallel stack plate, then the process cycle can be described as shown 4.
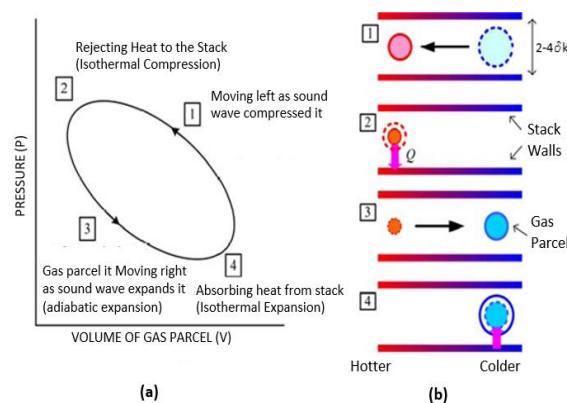
Figure 4. (a) Thermoacoustic cycle (b) Heat transfer processes in the stack [42] [11]

The working principle of thermoacoustic cooling consists of 4 stages that occur repeatedly. In Figure 4 shows the working stages of the system based on conditions of increase and decrease in temperature and pressure as follows [11]:

➤ Adiabatic Compression (1-2)

When the acoustic wave causes the gas package between the plate channel to move to the left, the compressed gas and the pressure increase

➤ Isothermal Compression (2-3)

The compressed gas package gets hotter than the stack wall, causing heat transfer from the gas to the stack wall because the stack temperature is lower and the volume of the gas parcel begins to shrink

➤ Adiabatic Expansion (3-4)

When the upright wave continues the cycle the gas package returns to the right direction, it will expand the air so the pressure drops again. The gas becomes more tenuous, this pressure drop will simultaneously reduce the air temperature so that the gas temperature is lower than the plate temperature

➤ Isothermal Expansion (4-1)

At this stage, heat moves from the stack to the gas because the gas absorbs heat from the stack wall and the gas package expands so that the temperature and pressure return to the initial state of the cycle.

From this stage it can be seen that the working principle of thermoacoustic refrigeration is different from the working principle of vapor compression refrigeration system.

4. Design Strategy

Many design procedures were carried out by several researchers such as Swift (1988), Wetzel, Herman (1996) and M.E.H Tijani (2001). The design method approach as done by Tijani in the Thermoacoustic refrigerator planning process and will be used as a reference for this research.
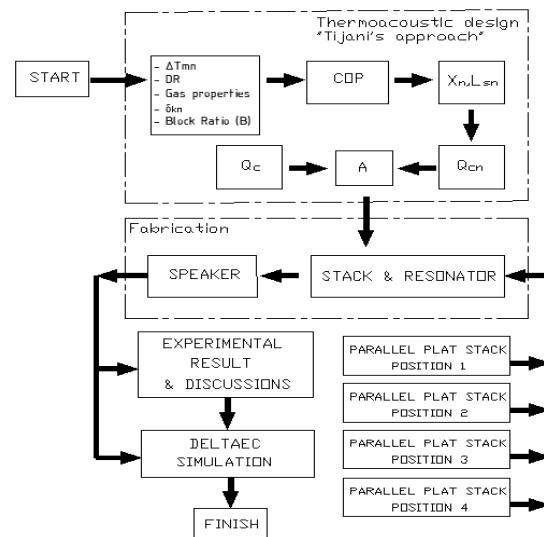
Figure 5. Design Strategy flow

This method will be used to determine design calculations in order to obtain the optimal dimensions and geometry of the test equipment, after which data analysis will be carried out and the test data will be compared with DeltaEC software simulation. Broadly speaking, the overall method of this research

will be carried out in accordance with the scheme as shown in Figure 5, because the limitations in the fabrication of heat exchanger devices in this study were not used.

5. Design Parameters

In determining the thermacoustic refrigerator as done by MEH Tijani there are several parameters that must be determined in advance, namely determining the amount of temperature difference (ΔTm) and desired cooling / cooling power (Qc) as MEH Tijani uses in designing thermoacoustic [12][13][14], so that we can determine the function of thermoacoustic to be applied to what cooling is suitable, from this parameter it will have an impact on the shape and size of the thermoacoustic refrigerator. $\Delta T_m = 75\ ^oK$; $T_m = 27\ ^oC$ ($300\ ^oK$); $Q_c = 40$ Watt (Cooling).

The selection of several operating parameters, working fluid and material from the stack and resonator are determined as follows.

5.1. Frequency & Resonator Length

The frequency will be determined at 245 Hz, where the frequency magnitude affects the wavelength value, while the wavelength (λ) is the distance between two identical points that are identical in waves and repeat. At certain sound wave frequencies, the waves resulting from interference will produce standing waves. This event is called resonance. The condition for the occurrence of resonance is given by

$$L = (2n\text{-}1)\ \lambda\ /\ 4 \tag{1}$$

Where L is the tube length and n = 1, 2, 3, ... is the harmonic or basic frequency resonance order, the frequency of the first, second and so on, while l is the wavelength. This wave is related to the length of the resonator tube So that the minimum L resonator length is generally for the closed tube side is λ / 4. The shape and length of the resonance is determined by the resonance frequency and minimal losses on the wall of the resonator tube. Resonator tube length usually varies with the acoustic wavelength produced, in previous studies determined the length of the resonator is $\lambda/4$, or $\lambda/2$ as done for example by Collard [9], because the frequency will determine the wavelength. This wavelength is equivalent to the length of the resonator that we need.

Determination of the wavelength to be more accurate in the resonance of upright sound waves as described by Taylor, et al (2011) that end correction factors must be used in the calculation of 0.33 times the diameter of the resonator [49]. Furthermore, the length of the resonator is determined equal to the magnitude of the wavelength plus the end correction factor that is given by

$$\lambda/4 + (0.33\text{\O}) \tag{2}$$

According to Tijani for the $\lambda/4$ resonator can be optimized by reducing the diameter of the right side with a large diameter ratio of $\text{\O}_1$ and small diameter $\text{\O}_2$ of 0.54. The speed of sound in air at a certain temperature is obtained from the following equation:

$$a = \sqrt{\frac{\gamma P_m}{\rho}} = \sqrt{\gamma RT} \tag{3}$$

$$RT = P_m/\rho \tag{4}$$

5.2. Thermal penetration depth

There are more than 2 parameters defined in the perpendicular direction of gas movement known as the thermal penetration depth (δk) and the viscosity penetration depth (δv) see figure 6.
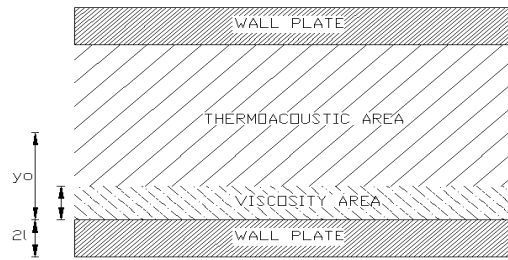
Figure 6. Illustration of the area δk and δv on the stack channel [40]

The thermal penetration depth is an estimate of the distance at which thermal can blend through the working fluid over a time interval of $1/\pi f$ (2/ω) which corresponds to the period (T) of the sound wave, remember that the period T is inversely proportional to frequency f.

$$T = 1/f. \tag{5}$$

- Gas thermal penetration depth (δk)

$$\delta_k = \sqrt{\frac{2k}{\omega . \rho_m . c_p}} = \sqrt{\frac{2K}{\omega}} \tag{6}$$

- Viscosity penetration depth δv

$$\delta_v = \sqrt{\frac{2\mu}{\omega \rho_m}} = \sqrt{\frac{2v}{\omega}} \tag{7}$$

- Solid Thermal penetration depth δs

$$\delta_s = \sqrt{\frac{2ks}{\omega . \rho_m . c_s}} = \sqrt{\frac{2Ks}{\omega}} \tag{8}$$

The wall plate thickness (2l) should be have 2δs < 2l; while the angular frequency (ω) is determined from equation 8 as follows:

$$\omega = 2\pi f \tag{9}$$

5.3. Average Pressure (P_m)

The average pressure that occurs inside the resonator is better made as large as possible because it is directly proportional to the amount of acoustic power and to the mechanical strength of the resonator material, also the greater average pressure will get the smaller thermal penetration depth. Because it does not use inert gas but only free air, the mean pressure in the resonator tube is 3.0 Bar.

5.4. Dynamic Pressure (Po)

Tijani said that to avoid nonlinear effects, the value of M (Mach number) must be limited to M ≈ 0.1, which was also suggested by Swift (1988) so that air movement keep remains linear.

$$M = P_o / \rho_m . a^2 \tag{10}$$

5.5. Drive ratio (D)
Drive Ratio (D) is the dynamic pressure ratio (Po) to the average pressure (Pm) or can be written below the equation

$$D = \frac{Po}{Pm} \tag{11}$$

So we get the Po value = 0.42 bar. While the amount of the Drive ratio (D) according to MEHTijani must be less than 3%, D ≤ 0.03 (Tijani, 2002), but in the calculation to make it a more realistic with the amount of pressure in the resonator tube, so this value is not used in terms of equation 11. It is obtained D value as follows:

$$D = Po/P_m = 0.14 \qquad \text{(dimensional)}$$

5.6. Working Gas
The working gas is one of the main parameter that must be considered because it will also affect the performance of the thermoacoustic system, the gas selection uses considerations such as has a high sound velocity, because it is important to remember that the speed of sound passing through different fluids will have a specific value in the speed of sound as well, other indicators are the gasses must have a low value of thermal conductivity and prandtl number [16].In this research will be used the air as a working gas.

Table 1. Gas properties (at P_{atm}, 27 ºC)

| Design Operating |
| --- |
| Thermal conductivity (k) = 0.0257   W/m.K |
| Sound Velocity (a) = 597,61   m/s (3 bar,300K) |
| Spesific Heat ratio fo air γ   = 1.4 |
| Heat capacity (Cp)   = 1007   J/Kg K |
| Dynamic Viscosity (µ)   = 1.87 x 10^{-5} Kg/s.m |
| Prandtl number (σpr)   = 0.72904 at 300K |
| Air density (ρ)   = 1.176   Kg/m3 |
| Constant (R) = 0.287   kJ/Kg.K (kPa-m3/Kg.K) |
| Gas Universal   (Ru)   = 8.314   kJ/Kmol.K |
| Molar Mass   (M_o)   = 28.970   Kg/Kmol |
| Molar Volume   (V_m)   = 0.0883   m3/Kmol |
| Thermal Difusiviy (K)   = 2.17 x 10^{-5} (m^2/s) |

6. Material Stack

Material stack must have a value of low thermal conductivity and heat capacity must be greater with a heat capacity of the gas work., MEH Tijani (2002) using a plate material Mylar as a stack on his research [12] also TJ Hofler (1986) using the material of camera roll films as a material in the form of a spiral stack [33]. Previous researchers in the early stages of development, for example GW swift, et al. (1990) still used stainless steel plate stack [29], JC Wheatley (1985) used tungsten as a plate material on the stack [37], but the use of stack using metal material was reduced currently because it refers to optimizing the performance of the engine the results of the years after that research that non-metal materials with low thermal conductivity values will increase efficiency. This research will use PVC Rigid Sheet or some known as Mica Film which is used for binding the book.

Table 2. PVC Rigid Properties

Thermal Conductivity (k_s) = 0.15 W/mK
Heat capacity (C_p) = 1260 J/Kg K
Solid Density (ρ_s) = 1400 Kg/m3 (1.4 g/cm3)

There are many types of stacks such as circular, parallel plate, triangle pores, etc. In this research will use parallel plate stack type according to Rott and MEH Tijani that this is the best shape. Parallel plate parameter illustration can be seen in figure 7 with the symbol definition; 2l is the thickness of the plate, 2yo is the distance of the air channel or the distance between the plates, Ls is the length of the stack, Π is the plate periphery
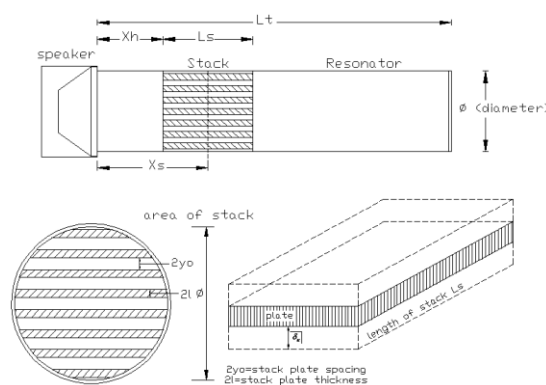
Figure 7. Parallel Plate Stack Parameters

According to Fig.7 parameter Π is given by

$$\Pi = \frac{A}{y_0 + 1} \tag{12}$$

Another important parameter is the Blokage ratio or porosity stack, with the equation:

$$B = \frac{y_o}{y_o + 1} \tag{13}$$

This parameter explains the presentation of the total area between solid and gas area, if the value of B is reduced then the thermoacoustic area will decrease but will increase the number of gas particles in the system.

   Various choices of stack shapes that we might be able to use such as parallel plate, circular pore, array pin, triangle pore. The stack shape as illustrated in the Rott function diagram (see figure 8). Figure 8 shows the Real and imaginary parts of the Rott function (ƒk) of several shapes of the stack as a function of the ratio of the hydraulic radius (rh) and the thermal penetration depth (δk), from the visible pin shape and parallel plate shape is the most effective form used , the use of array pins in this study is not used because it is very difficult in fabrication so it will only use a stack with parallel plate, As we seen from Figure 8, for parallel plates the hydraulic radius value (rh = yo) so that the lm value (-ƒk) from Figure 8 below has a value for rh/δk = yo/δk.
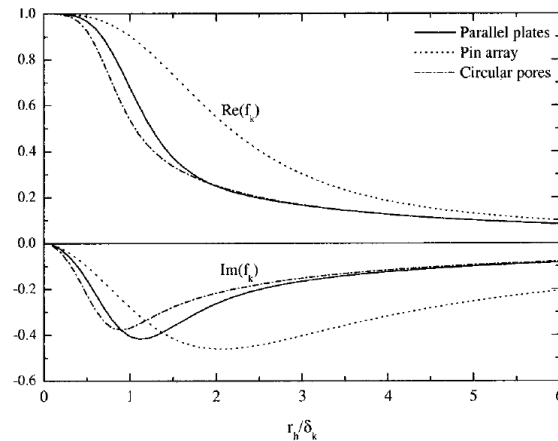
Figure 8. Rott's Function Diagram as a function of the hydraulic radius (rh) and thermal penetration depth (δk).

7. Stack Parameter Design

There are three stack design parameters namely Normalized stack position (Xn), Normalized stack length (Lsn) and the third is the cross section of the stack (A). See figure 7 as a reference notation for determining the stack and resonator dimensions. Generally the cross-sectional area (A) of the resonator tube is the same as the cross-sectional area of the stack. From the three parameters above can be made the following equation:

$$Xn = kv \cdot Xs \tag{14}$$

$$Lsn = kv \cdot Ls \tag{15}$$

While the Wave number is determined by the following equation:

$$kv = \frac{\omega}{a} \tag{16}$$

Some other parameters for stack design are

$$\Delta T_{mn} = \Delta T_m / T_m \tag{17}$$

Usually the average Temperature (Tm) works at room temperature of around 27ºC or 300ºK,

a.Parallel plate Stack type

Referring to figure 7, the dimensions of the plate thickness (2l) and the distance between plates (2yo) will be determined. The relationship between 2yo and 2l is determined by equation 13 so that the value 2l becomes:

$$2l = 2y_o \left(\frac{1}{\beta} - 1 \right) \tag{18}$$

Blockage Ratio value itself according to Iksan, et al (Iksan, 2013) will improve performance with increasing values, taken in this study by 0.778, whereas when referring to the graph of Rott's function as illustrated in Figure 8, for parallel stack plate selection types, has a maximum lm (-*f*k) value with rh/ δk =1.1, and with a hydraulic radius *(rh) = yo*, then from the maximum point graph the parallel plate stack type is rh/δk = yo/ δk= 1.1, because (rh) Radial radius is the middle distance from the free area for gas media, so for stack type parallel the distance between plates is equal to 2yo,

So that the theoretical value 2yo = 1.1 x 2 = 2.2 δk. This is also according to the optimum distance suggestion based on Arnott (1991) which is about 2.2 δk, while Tijani (2002) suggests 2yo = 3δk, while Swift (1998) mentions about 4δk for 2yo, because the reason for uncertainty is that Arnot is only based on theory, while Tijani & swift are based on experimental test results, but this value is still proportional to the range (2 to 4) δk and this is also in accordance with the advice of Wheatley (1985). In this study the author uses 2.1δk according to the graph due to availability the plate spacing.

b. Stack Length (Ls) & Stack Diameter
M.E.H Tijani (2002) uses Figure 9 to explain the performance of the stack calculation as the Normalized function of the stack length (LSn) and the Normalized Distance Stack (Xn).
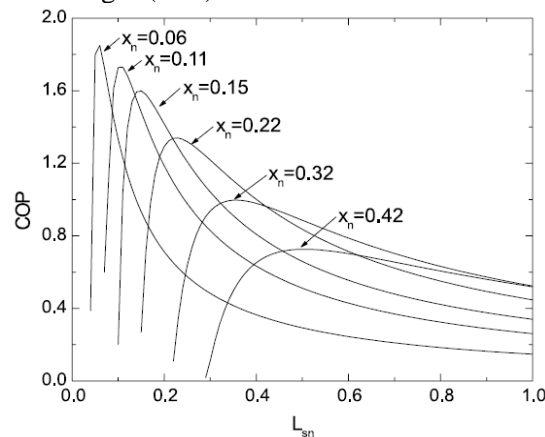
Figure 9. Performance calculation stack, as a function of the Normalized Stack Length (Lsn) & Normalized Distance Stack (Xn) [12]

Refer to figure 9, if the position at Xn = 0; defining the position of the loud speaker as (antinode pressure), in other words the smaller the Lsn value means the closer to the speaker, then based on the number of experimental cases the COP value shows the maximum limit that can be achieved from each stack position optimally, as if the normal value stack position (Xn) increases which means the position of the stack distance is also large, while the COP value will decrease. We will use Xn=0.11, and Lsn=0.135.

8. Performance and Efficiency

Dimensional Determination of the thermoacoustic heat rate (Qcn) that occurs through the gas medium and stack material around the stack area, and the dimensions of the acoustic power (Wn) can be determined using the equation as used by MEH Tijani (Tijani, 2001) and (Hao, 2006). Dimensional Thermoacoustic heating rate / Normalized Cooling power (Qcn).

$$Q_{cn} = -\frac{\delta_{kn}D^2 sin((2x_n))}{8\gamma(1+\sigma)\Lambda}\left(\frac{\Delta T_{mn}tan(x_n)}{(\gamma-1)BL_{sn}}\frac{1+\sqrt{\sigma}+\sigma}{1+\sqrt{\sigma}} - (1+\sqrt{\sigma}-\sqrt{\sigma}\delta_{kn})\right) \tag{19}$$

While the values of Λ and δkn have the following equation:

$$\delta_{kn} = \delta_k / y_o \tag{20}$$

$$\Lambda = 1 - \sqrt{\sigma}\delta_{kn} + \frac{1}{2}\sigma\delta_{kn}^2 \tag{21}$$

where, y_o = half the distance between the stack plate walls. Normalized acoustic power (Wn) is given by

$$W_n = \frac{\delta_{kn}.L_{sn}D^2}{4\gamma}(\gamma - 1)B \cos (X_n)^2 \left[\frac{\Delta T_{mn} \tan (X_n)}{BL_{sn}(\gamma - 1)(1 + \sqrt{\sigma})\Lambda} - 1\right]$$
$$- \frac{\delta_{kn}L_{sn}D^2 \sqrt{\sigma} \sin (X_n)^2}{4\gamma} \frac{}{B\Lambda} \qquad (22)$$

Note: All trigonometri function in radian not degree. Relationship between Q_{cn} and Wn

$$Q_{cn} \qquad = Q_c / P_m.a.A \qquad\qquad (23)$$

$$Wn \qquad = W/ P_m.a.A \qquad\qquad (24)$$

With the substitution of Q_{cn} and Wn values, we will get the stack cross-sectional area (A). The performance of the thermoacoustic refrigerator is determined by the COP value or the Coefficient of performance, the maximum COP that can be produced is given in equation 25, namely;

$$COP = \frac{T_c}{T_{h-T_c}} \qquad\qquad (25)$$

COP for refrigeration systems can also be determined by the equation;

$$COP = \frac{Q_{cn}}{W_n} \qquad\qquad (26)$$

With reference to Figure 10, the results of the calculation will be summarized as follows:

Table 3. Calculation results

a = Sound Velocity = 597,61 m/s
λ = Wave length = 2,439242 m
kv= Wave number = 2.57457
D = Drive ratio = 0.14
P_o = Dynamic pressure = 0,42 bar
P_m = Mean Pressure = 3.0 bar (3.0 x 10^5 Pa)
ΔT_{mn} = Normalized Temperature differ.= 0.25
ΔT_m = Temperature different = 75 °K
T_m = Mean Temperature = 300 °K
δ_k = Thermal penetration depth= 0.168 mm
δ_{ks} = Solid Thermal penetr.depth=0.0105mm
δ_v = Viscosity penetration Depth= 0.1436mm
ω = Angular frekuensi; $2\pi f$ = 1538.6 rps
δ_{kn} = Normalized thermal penetr.depth=0,961
Q_{cn} = 4.8176 x 10^{-5} (dimensional)
Wn= 5.5366 x 10^{-5} (dimensional)
COPtheory = 0.870141
Wtheory = Power speaker = 45,9696 Watt

Stack Parameter
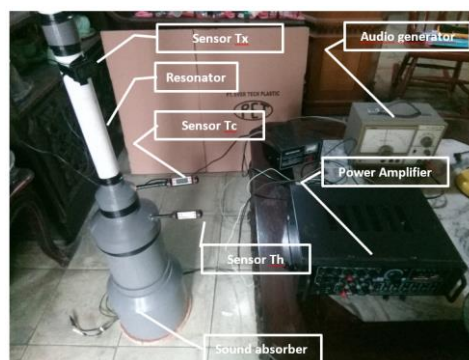A = Cross Section area of Stack = 0.0046 m^2
B = Blockage ratio = 0.778
Ø = Diameter of Stack & Large tube = 3 Inch
Ø$_2$= Diameter of small tube = 1 1/2 Inch
Lt = Resonator length= 0.61 m = 61 cm
Xn=0.11 ; Lsn = 0.135
Ls = Stack length = 0.52 meter ≈ 5,2 cm
2yo = Stack plate spacing = 0.35 mm
2l = Stack plate thickness = 0.1 mm
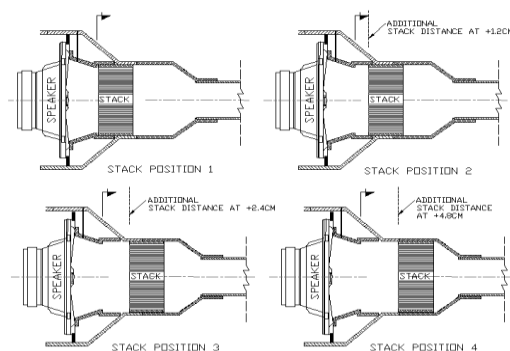
9. Fabrication & Experimental Setup
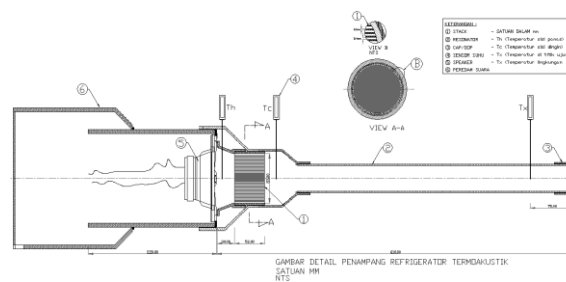
(a)

(b)

Figure 10. (a)Thermoacoustic Refrigerator detail, (b) Thermoacoustic devices

The Stack Posisition can be describe in figure 11, that the test will be devided to be fours at different distances also the sensor location was placed based on figure 10.According to Table 3 the parallel plate Stack was made as can be seen at figure 12.
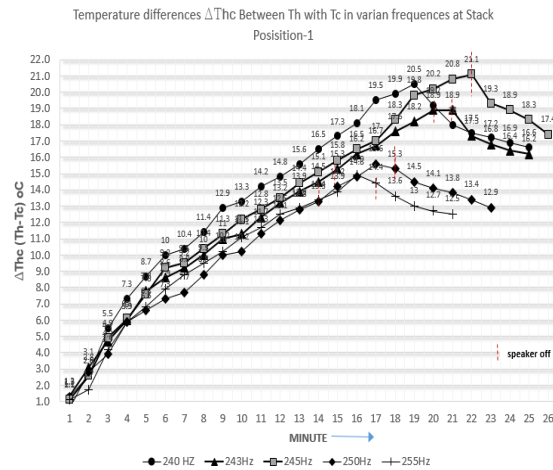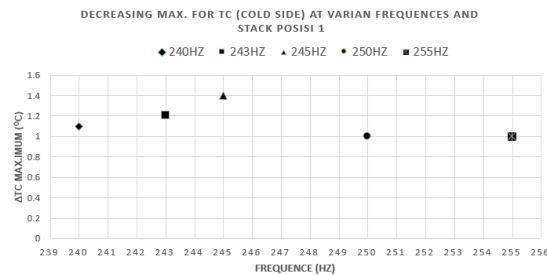

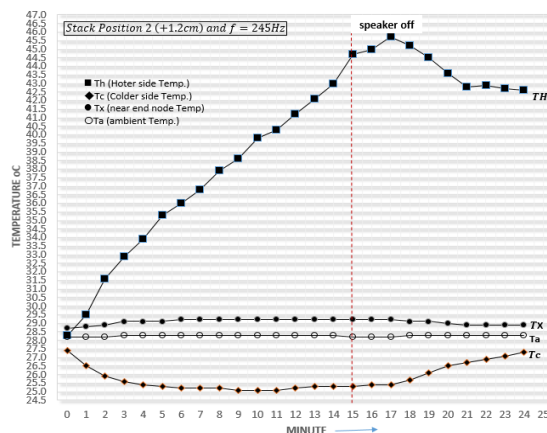**Figure 11.** Stack Position

Figure 12. Stack Fabrication

10. Results and Discussion

**Figure 13.** Temperature vs Minute at varian frequencies in Stack Position 1

**Figure 14.** Decrease of temperature maximum Tc at varian frequencies in Stack Position 1

In fig. 13 and fig.14 the test has been conducted at stack position 1 with initial frequence 245Hz, also above and below from intial frequence are 240Hz, 243Hz, 250Hz and 255Hz respectively has tested. The results can be seen that the 245Hz has a value with optimum result. So the next it will be used to be initial frequence to applied to other stack position testing.
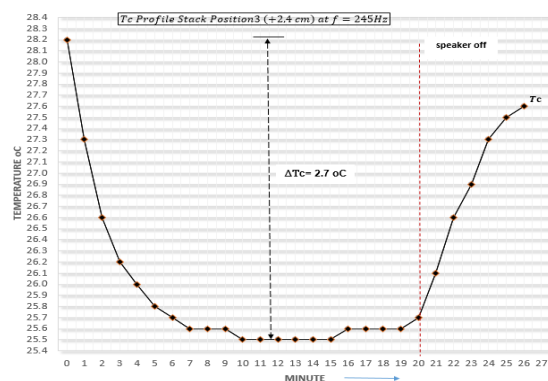

Figure 15.Temperature vs Minute at *f*=245Hz in Stack Position 2
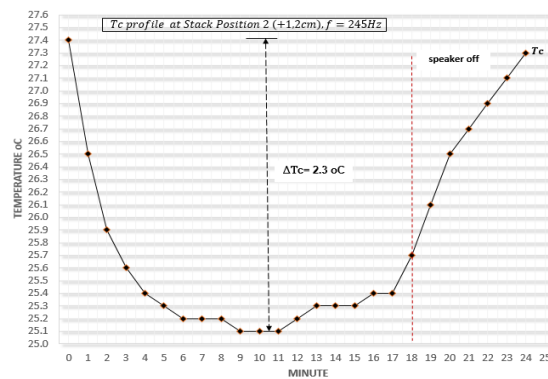
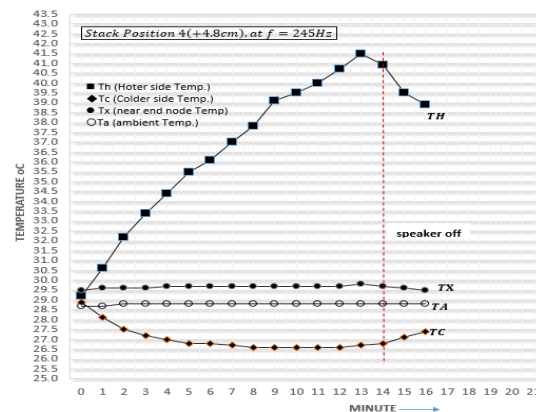**Figure 16.**Temperature colder side (Tc) vs Minute at *f*=245Hz in Stack Position 2
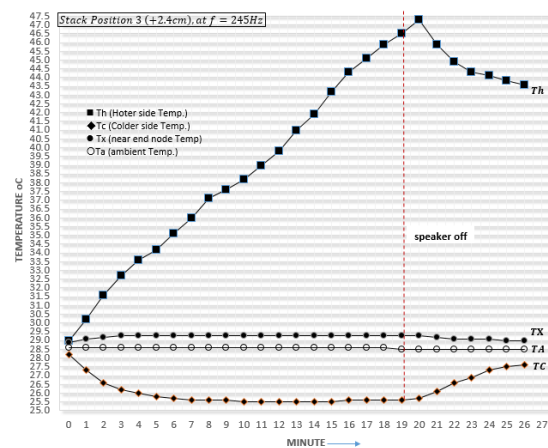
Figure 17.Temperature vs Minute at *f*=245Hz in Stack Position 3

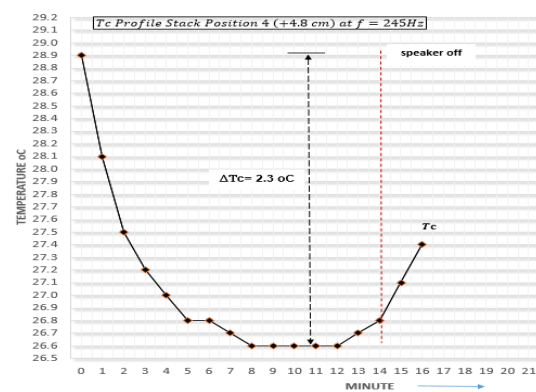**Figure 18.**Temperature colder side (Tc) vs Minute at *f*=245Hz in Stack Position 3

Fig.17 to fig.19 and fig.21 has been tested and the results shows the optimum value that can be achieved on this experiment that the Stack position 3 is the best position. The value of decrease of temperature Tc (Colder side) maximum around 2.7°C for 10 minute.
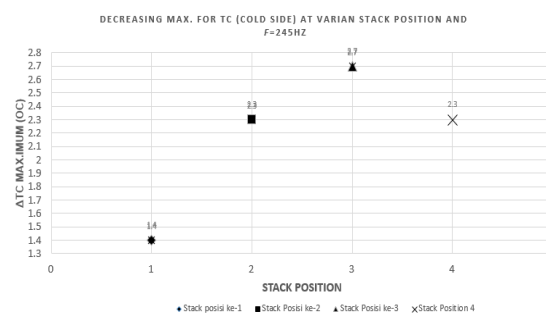
Figure 19.Temperature vs Minute at *f*=245Hz in Stack Position 4

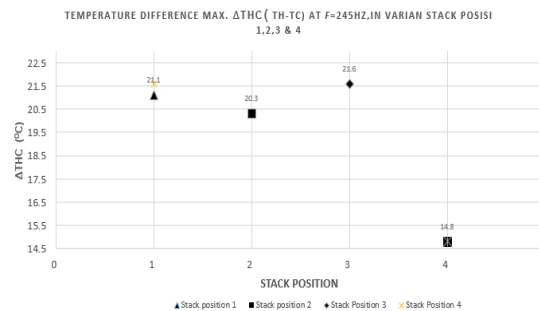Fig.21 has described that the position 3 is the best position than others, the value of temperature difference (Th-Tc) around 21.6°C in 20 minute, perhaps this value can be used for heatpump needed for other research.

**Figure 20**.Temperature colder side (Tc) vs Minute at *f*=245Hz in Stack Position 4

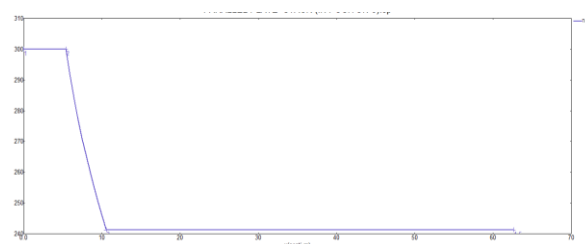**Figure 21.**Temperature colder side (Tc) vs Minute at *f*=245Hz in Stack Position 1- 4

Figure 22.Temperature difference maximum (Th-Tc) at *f*=245Hz in Stack Position 1- 4

-*DeltaEC Simulation*

From the Stack position 3 with *f*=245Hz, the DeltaEC segment model is made and the geometry dimensions will be followed acoording to fig.10a.
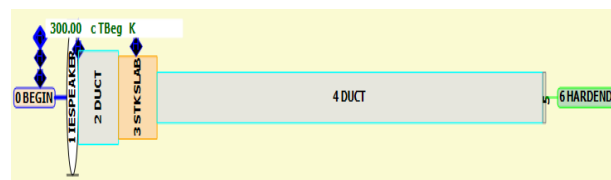
Figure 23.DeltaEC Geometry model

Figure 24. DeltaEC result for Temperature distribution along the resonance tube

In Fig 23. Shown that the distribution temperature on the stack it's going down, with the maximum Colder side Temperatur end of stack (Tc) 300 °K to be 241°K, so the simulation is given the large number value for decrease of temperature deltaTc around 59°K, if compared with the experiment result the deltaTc only 2.7°C, but need to know that on this software there is no explanation about how many time the result Tc end of stack will be taken., fig 24. Also described about the value of temperature (T) and pressure (P) distribution along the resonance tube, also the value of oscillatory volume flow rate (U) and Acoustic Power flow (E).
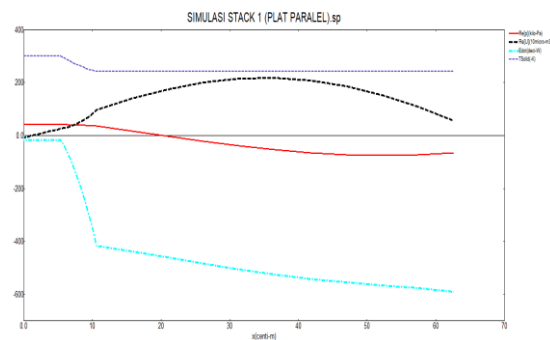
Figure 25.DeltaEC result for Temperature (T); Pressure (P);(U) oscillatory volume flow rate; E (acoustic power flow)

11. Conclusions

Thermoacoustic refrigerator is one of the technologies that can be considered as a "green technology" to the future. The precision of the Stack and resonator domensions will have huge impact of the result also the right position stack along the resonance tube.

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