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ENVIRONMENTALLY FRIENDLY REFRIGERATION WITH THERMOACOUSTIC

SISTEM PENYEJUKAN MESRA ALAM DENGAN THERMOAKUSTIK

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ABSTRACT

ENVIRONMENTALLY FRIENDLY REFRIGERATION WITH THERMOACOUSTIC

(Keywords : Refrigeration, Thermoacoustics, Non CFC's, Waste Heat)

Use of CFC-contained systems has caused severe environmental hazards that have researchers looking for alternatives. Previous studies have shown that thermoacoustic technology is suited a candidate for conventional vapor compression cooling system in particular for special uses. In this research, theoretical, numerical and experimental studies were completed to identify optimum operating conditions for the design, fabrication, and operation of a thermoacoustic refrigerator. The system uses no refrigerant or compressor, and the only mechanical moving part is the loudspeaker connected to a signal generator that produces the acoustics. Numerical simulation found that mixtures of Helium and other noble gases do produce greater thermoacoustic effects as reported theoretically and experimentally. A series of tests both in the laboratory and at selected sites with a system fabricated under Vot 71891 (Padang Kawad UTM, Rumah Alumni UTM, and outside tutorial room) found that the thermoacoustic effects were consistent and reliable. The system fabricated with this grant is made of copper and aluminium with a sinusoidal section to reduce power loss and can operate up to a maximum of 10 bar. The system can be taken apart if different stack geometry or material is to be studied.

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ABSTRAK

SISTEM PENYEJUKAN MESRA ALAM DENGAN THERMOAKUSTIK
(Katakunci : Penyejukkan,Thermoakustik,Tanpa CFC, Haba Buangan)

Penggunaan sistem dengan CFC yang menyebabkan kesan teruk ke atas sekitaran membuatkan para penyelidik di seluruh dunia mencari suatu alternatif. Kajian-kajian asal telah membuktikan bahawa teknologi termoakustik mampu untuk menggantikan sistem penyejukan lazim pemampatan wap untuk penggunaaan tertentu. Dalam kajian ini. kaedah teori, eksperimen dan berangka dijalankan untuk mengenal pasti keadaan operasi yang optimum untuk reka bentuk, fabrikasi, dan operasi penyejukan termoakustik. Sistem ini tidak menggunakan cecair penyejuk atau pemampat; alat bergerak hanyalah sebuah pembesar suara yang disambung kepada signal generator yang menghasilkan gelumbang akustik. Kaedah berangka menunjukkan bahawa campuran Helium dan gas lengai lain dapat menghasilkan kesan termoakustik yang lebih baik seperti yang diperkatakan teori dan diperolehi dalam laporan eksperimen. Beberapa siri ujikaji di dalam dan luar makmal dengan sistem termoakustik dari Vot 71891 (Padang Kawad UTM, Rumah Alumni UTM, dan di luar bilik tutorial) menunjukkan bahawa kesan termoakustik adalah konsisten dan boleh diharap. Sistem yang dibuat dengan geran penyelidikan ini adalah dari kuprum and aluminum dengan bahagian berbentuk sinus untuk mengurangkan kehilangan kuasa dan ia dapat beroperasi sehingga 10 bar. Sistem ini juga boleh dibuka sekiranya geometri tindan yang lain perlu diuji untuk kajian.

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CHAPTER 1 - INTRODUCTION

The first and second laws of thermodynamics place an upper bound on the efficiency of heat engines. If T_H and T_C are the hot and cold thermal reservoirs, respectively, and Q_H and Q_C the associated heat flows with W the work flows as shown in Figure 1.1, in the usual case of cyclic engines operation, Q_H and Q_C and W are time averaged powers. The operation is assumed steady-state, so that the time-averaged state of the engine itself does not change. The first law of thermodynamics states that

$$Q_H - Q_C = W \qquad (1)$$

The second law states that the entropy generated by the system must be positive or zero. Since the engine is in (time averaged) steady state, the net entropy increase in the reservoirs is

$$Q_C/T_C - Q_H/T_H \geq 0, \text{Heat Engine} \qquad (2)$$

$$Q_H/T_H - Q_C/T_C \geq 0, \text{Refrigeration} \qquad (3)$$

For the prime mover, the efficiency of interest is $\eta = W/Q_H$. Combining Equations (1) and (2) to eliminate Q_c,

$$\eta = W/Q_H \leq (T_H - T_C)/T_H \qquad (4)$$

The temperature ratio in Equation (4) is called the Carnot efficiency, η_c. It is the highest efficiency that a prime mover can achieve. Meanwhile for a heat pump, the efficiency is called the coefficient of performance, $COP = Q_C/W$, reflecting the fact that Q_C is the desired output of the refrigerator. Combining Equation (1) and (3) to eliminate Q_H,

$$COP \leq T_C/(T_H - T_C) \qquad (5)$$

Thermoacoustic systems operate in a similar manner with the heat engine generating acoustic power and the heat pump requiring acoustic power. The efficiency and COP, however, are not derived similarly.

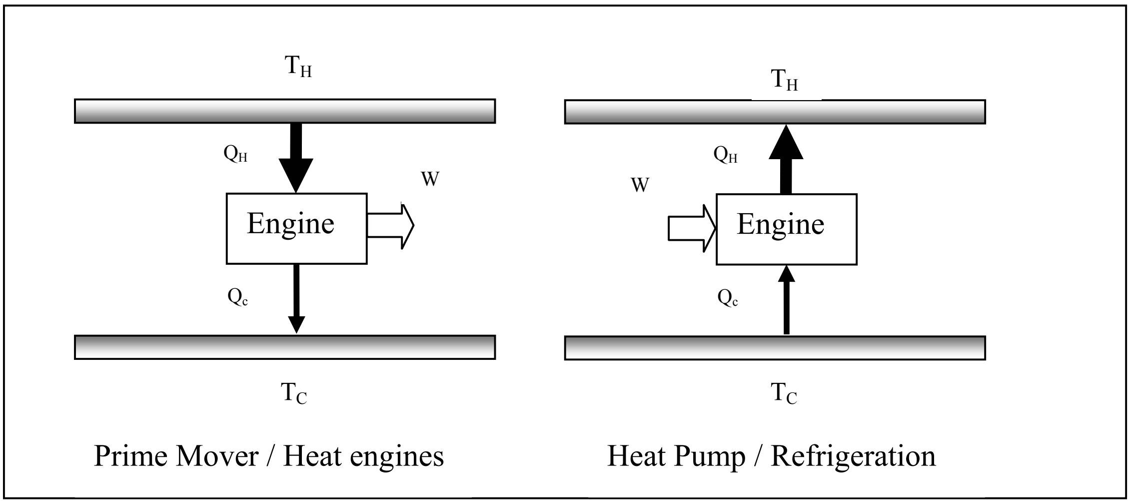


Figure 1.1: Two Types of Heat engines, Prime Mover and Refrigerator

1.1 THERMOACOUSTIC THEORY

Thermoacoustic effects had been observed for a long time, with the two most famous devices, the Sondhauss tube and Rijke tube being described in 1850 and 1859 respectively (Wheatley et.al., 1985). However, a theoretical explanation to the thermoacoustical effects observed in these devices is only available through Lord Rayleigh whose discussion is mostly qualitative. According to Rayleigh, heating and cooling could create acoustic power "if heat be given at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction" and the heating and cooling could be created by an acoustic wave (Backhaus and Swift, 2002). A quantitative theoretical explanation is available only by 1970s through the works of Nikolaus Rott. These theories are later used in the development of a thermoacoustic heat engine.

Thermoacoustic heat engines are able to function as a prime mover or a heat pump owing to the nature of the thermoacoustical phenomena where acoustic power is generated if oscillatory thermal expansion and contraction is created and oscillatory thermal expansion and contraction could be caused by a temperature gradient. The difference of the function of the heat engine is therefore dependant on whether thermal or acoustic power is given. Acoustic power is provided through an acoustic driver while thermal power or heat is provided through the heat exchangers.

Thermoacoustic heat engines are further divided into two categories, standing-wave engines and traveling-wave engines. The traveling wave engine is better known as a Stirling engine (Backhaus and Swift, 2002), while thermoacoustic heat engines normally refers to the standing wave heat engine. In standing-wave engines, a standing wave is generated within the resonator and a stack with moderately spaced plates is introduced in the resonator to ensure a poor but nonzero thermal contact. Fluid in traveling-wave engine oscillates in a traveling wave and the plates in the stack are closely spaced to ensure a perfect thermal contact between fluid and stack (Swift, 1988)

Simple thermoacoustic refrigeration (heat pump) is shown in figure 1.2.

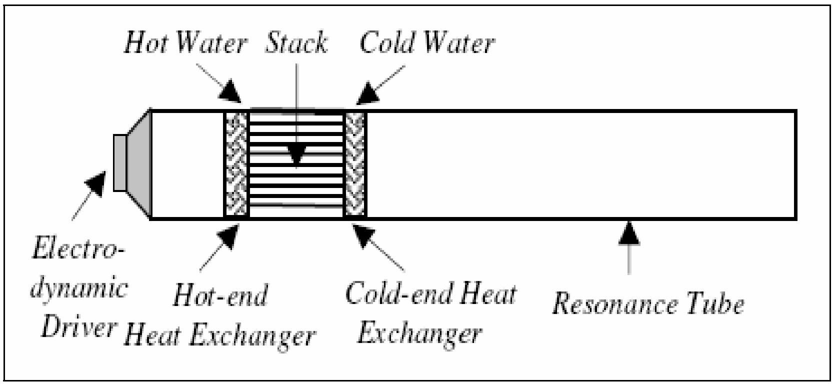


Figure 1.2: Thermoacoustic Refrigeration

The thermoacoustic effect occurs in the stack region and requires the presence of two thermodynamics media i) Stack ii) working fluid (gases). This region also calls as thermoacoustic core. To get an extra understanding about the thermoacoustic theory, see figure 1.3.

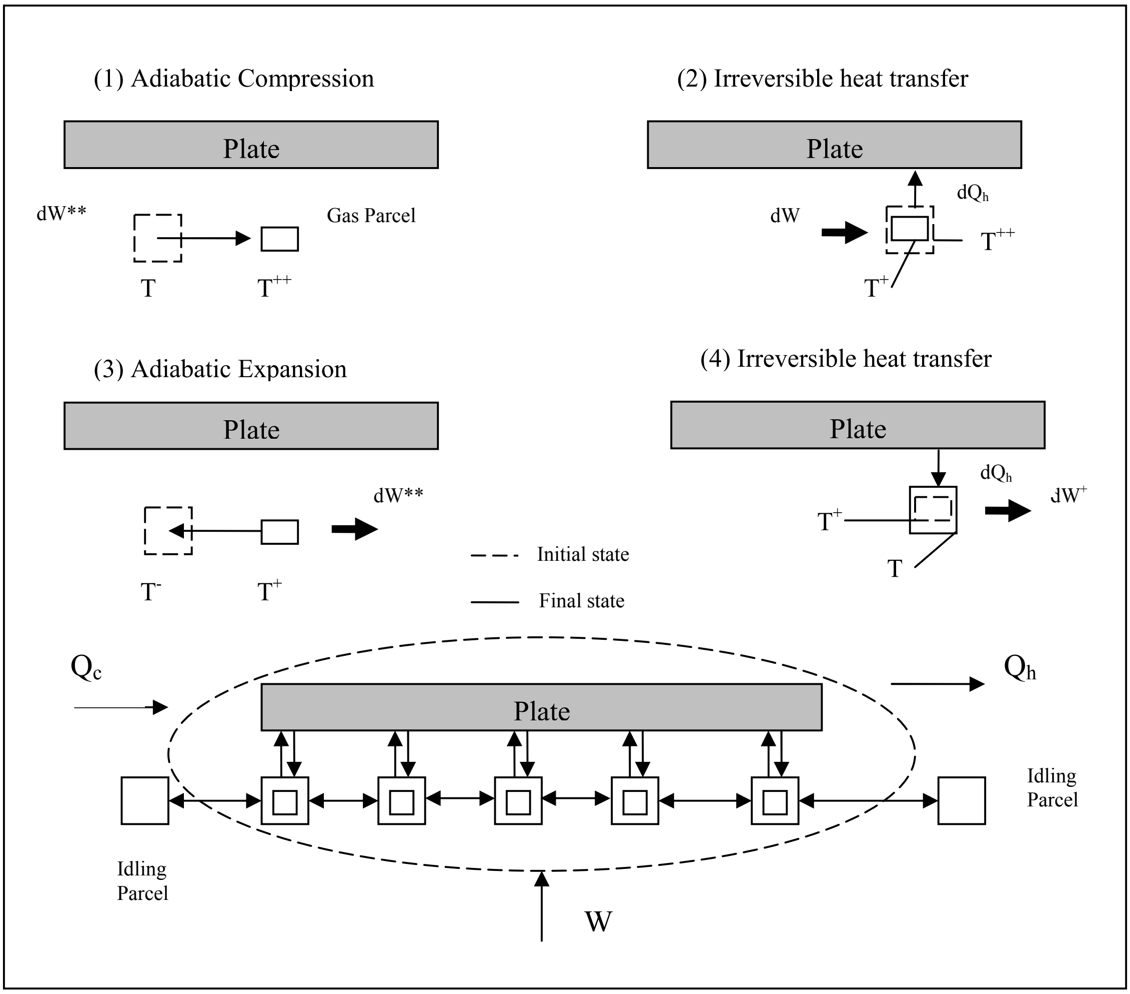


Figure 1.3: Transport of heat along a stack plate

The cycle consists of two adiabatic steps (1 & 3) and tow isobaric steps (2 & 4). The acoustics standing wave moves the gas parcel forward, the gas parcel is adiabatically compressed causing its temperature to rise, let's say by tow arbitrary units to reach the temperature T^{++}, as indicated in figure 1.3, step (1). At this stage the gas parcel is warmer than the stack plate and irreversible heat transfer from the working fluid towards the stack plate takes place. In step (2), the gas parcel cools down by one arbitrary unit to the temperature T^{+}. In the process of adiabatic expansion, the gas parcel moves back to its initial location and cools down by two arbitrary units to reach the temperature T^{-}, as indicated in step (3). At this stage the gas parcel is colder than the stack plate and irreversible heat transfer from the stack plate towards the gas parcel takes place in the fourth step. During the described cycle, the gas parcel has returned to its initial position and initial temperature T and therefore the cycle can start again.

Since there are many gas parcels moving along the stack plate, and heat that is dropped by one gas parcel, is transported further by the adjacent parcel, a temperature gradient develops along the stack plates.

1.2 PROBLEM STATEMENT

Sources have mentioned that Pakistan has managed to produce acoustic waves from waste heat generated by biomass combustion but there are no current published papers to that effect. Research is currently being done in the USA, Europe, South Africa and Japan both experimentally and numerically on both the thermoacoustic heat engine and refrigeration systems. Numerical works are few and limited to the 2-plate region. No recorded data on thermoacoustics have been established in Malaysia. My PhD dissertation (University of New Hampshire, USA, 2001) has successfully simulate the generation and progression of acoustic waves in a chamber with and without the heat exchanging plates. This research intends to perform numerical study on gas mixtures which theories have explained their superiority in producing greater thermoacoustic effects. The study will design, fabricate, and test an optimized thermoacoustic refrigerator which utilizes waste heat using Helium as the primary working fluid.

1.3 OBJECTIVE AND SCOPE OF STUDY

1. To study further the development of the acoustic waves from waste heat.
2. To develop application for refrigeration system from the acoustic waves generated from

CHAPTER 2 - DESIGN STRATEGY

There were many design strategy proposed by many authors such as Swift (1988), Wetzel and Herman (1996), and Tijani (2001). The most simple design approach is that of Tijani's which is being used here in the design of the thermoacoustic refrigerator

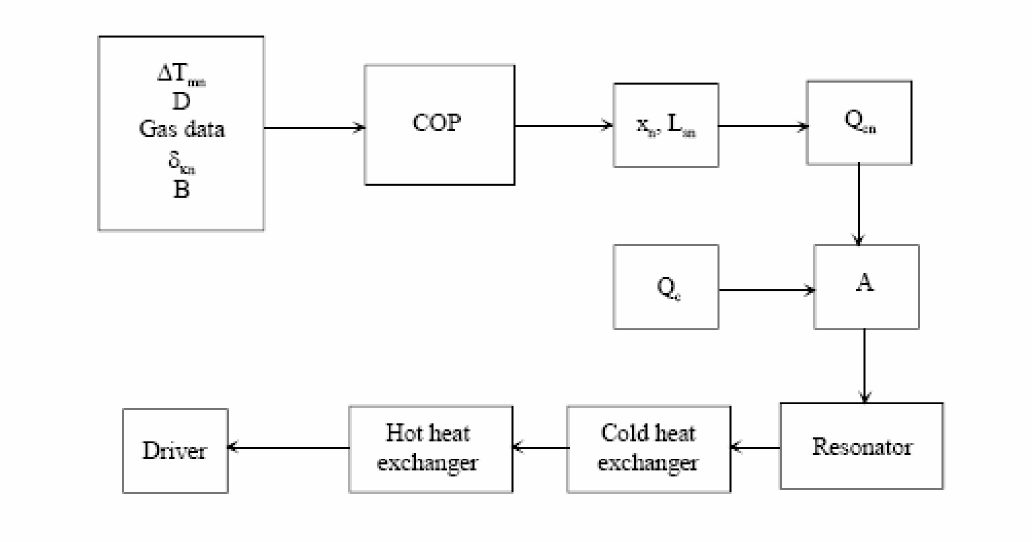


Figure 2.1: Design Procedures according to Tijani's approach

2.1 CHOOSING OPERATING PARAMETERS

Listed below are the steps in selecting the operating parameters for the thermoacoustic refrigerator.

1. First chose the temperature gradient (ΔT_m) and the cooling power ($\dot{Q}_{cn}$) wanted,

   ΔT_m = 75K and $\dot{Q}_{cn}$ = 5W
2. Then we state the available operating frequency (f) in here we choose f = 400Hz
3. Tijani's mentioned that to avoid nonlinear effect, M, Mach number has to be limited to M ≈ 0.1.

$$M = \frac{p_o}{\rho_m a^2} \qquad (1)$$

Where:

M = Mach number

p_o = Dynamic Pressure

ρ_m = Gas density (take note that the different between p_m and ρ_m)

a = sound velocity

With M = 0.1, the Drive Ratio should be less than 0.03, D ≤ 0.03. Then we choose D = 0.02

$$D = p_a / p_m \qquad (2)$$

Where:

D = Drive Ratio

p_o = Dynamic Pressure

p_m = Average Pressure

The Average Pressure, p_m should be as large as possible. Due to difficulties in fabrication we choose p_m = 10bar. Then we can decide the dynamic pressure, p_o using equation (2). So we get p_o = 0.2bar

4. Then we choose the working gas. Here we choose Helium as the working gas. This is because Helium has the highest sound velocity, a, and thermal conductivity, K of all inert gases.
5. The mean temperature, T_m is set to be T_m = 300 K and then calculate the Normalized temperature difference, ΔT_{mn} by this equation below,

$$\Delta T_{mn} = \Delta T_m / T_m \qquad (3)$$

Where:

ΔT_{mn} = Normalized temperature difference

ΔT_m = Temperature gradient

T_m = Mean temperature

Here we will get ΔT_{mn} = 0.25

Table 2.1 : List of operating parameters

Operating Parameters
Operating frequency : f = 400 Hz Average pressure : P_m = 10 bar Dynamic Pressure : p_o =0.2bar

Drive Ratio : D = p_o/p_m = 0.02
Mean Temperature : T_m = 300 K
Temperature gradient: ΔT_m = 75K
Normalized temperature difference : ΔT_{mn} = 0.25
Cooling power: $\dot{Q}_{cn}$ = 5W

6. There were a number of parameters that should been decided early such as gas type, resonator material and stack material.

Table 2.2 : List of working gas parameters

Working Gas Parameter
Thermal Conductivity : K = 0.13 W/m.K
Sound velocity : a = 935 m/s
Ratio of isobaric to isochoric specific heats : γ = 1.67
Heat capacity : c_p = 5200 J/kg.K
Gas density : ρ_m = 1.9 kg/m^3
Dynamics viscosity : μ = 1.7 x 10^{-5} kg/s.m
Prandtl Number : σ (Pr) = 0.68

STACK DESIGN

7. Design of the stack is complex. Here we have also used Tijani's approach.
8. The stack material must have low thermal conductivity, K_s and heat capacity c_s larger than the heat capacity of the working gas, c_p. So Mylar is chosen as its has a low heat conductivity, K_s = 0.16 W/m.K
9. There are many types of stack; parallel, circular, pin array, triangular etc. due to fabrication reason; we choose the parallel plates type of stack. For the parallel plates stack we must have that $r_h = y_o$.

10. The thermal penetration depth (δ_k) and viscous penetration depth (δ_v) are given by,

$$\delta_k = \sqrt{\frac{2K}{\rho_m c_p \omega}} \qquad (4)$$

Where

K = Gas thermal Conductivity

ρ_m = Gas density

c_p = Gas heat capacity

ω = angular frequency

$$\omega = 2\pi f \qquad (5)$$

Where:

f = Operating frequency

$$\delta_k = \sqrt{\frac{2\mu}{\rho_m \omega}} \qquad (6)$$

Where:

μ = Gas Viscosity

11. Using the above equations we will get the δ_k = 0.1mm and δ_v = 0.08mm. as can see from figure below, for parallel plates stack lm($-f_k$) has a maximum for r_h/δ_k = y_o/δ_k = 1.1

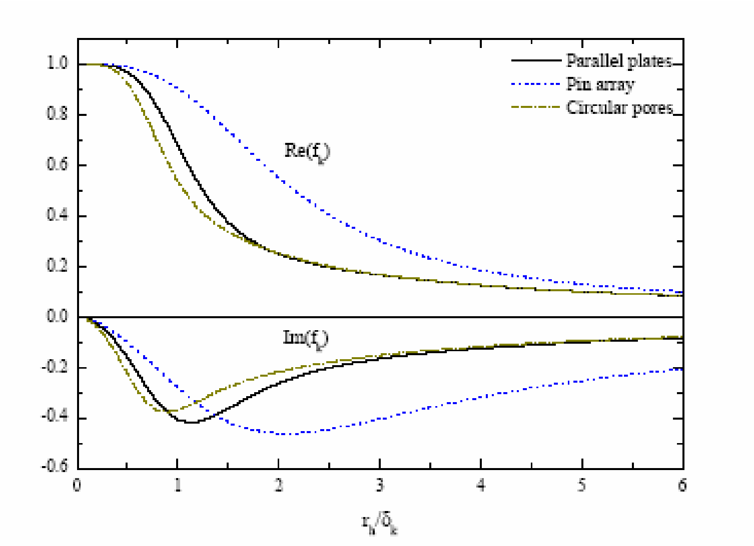


Figure 2.2: Imaginary and real parts of the Rott function f_k as function of the ratio of the hydraulic radius and the thermal penetration depth.

12. From here we can get y_o = 1.1mm or $2y_o$ = 0.22mm.Wheatley has stated that in order not to alter the acoustics field, a spacing of $2\delta_k$ to $4\delta_k$ must be used. So we choose $2y_o$ = 0.3mm

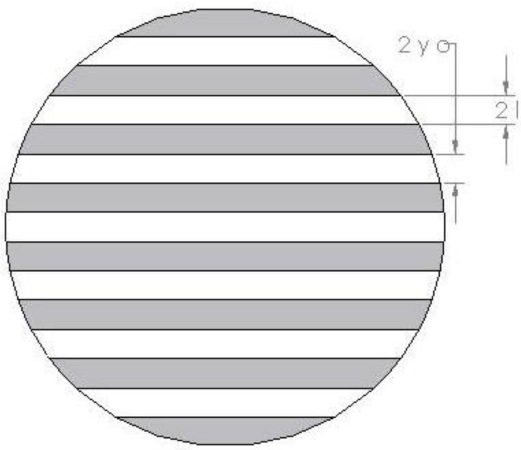


Figure 2.3: Illustration of cross sectional view of parallel plate stack, the plates are 2l thick and are $2y_o$ spaced

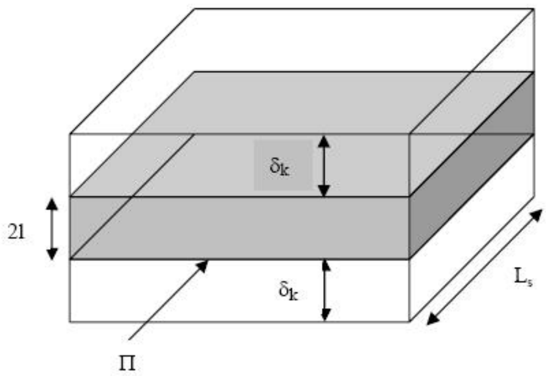


Figure 2.4: A plate of stack with the parameters

13. The blockage ratio or also known as porosity of the stack, B is given by

$$B = \frac{y_o}{y_o + l} \qquad (7)$$

Where:

l = Half stack plate thickness

14. The porosity is B = 0.75 like been suggest by Tijani's. So from equation (7) we will get l = 0.05mm.($2l$ = 0.1mm)
15. From the figure below we set the value of the normalized stack center, x_n=0.22. This is because a value greater than that is difficult to fabricate. So when we choose x_n=0.22, the normalized stack length, L_{sn} should be about L_{sn} = 0.22.

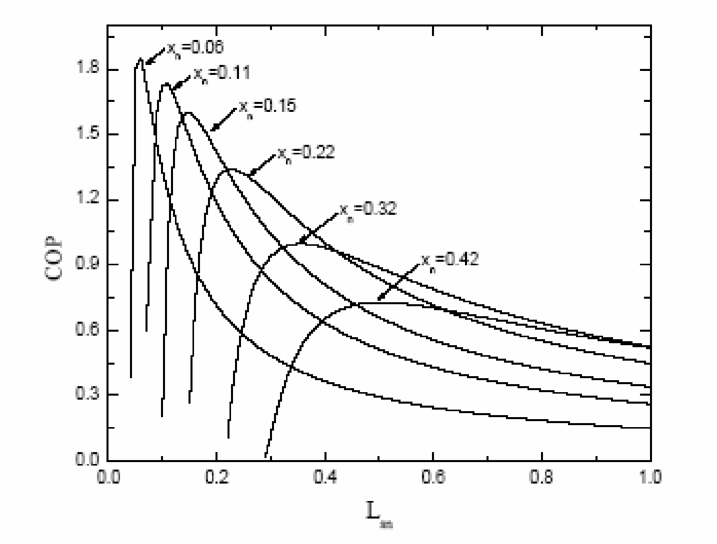


Figure 2.5: Performance calculations for the stack, as a function of the normalized stack length L_{sn} and normalized stack center x_n.

16. Equation (8) and (9) are the relations between Normalized stack operation and stack operation.

$$L_{sn} = kL_s \qquad (8)$$

Where:

L_{sn} = normalized stack length

L_s = Stack length

k = Wave number

$$x_n = kx_s \qquad (9)$$

Where

x_n = normalized stack center

x_s = stack center

k = Wave number

17. Wave number is given by the equation:

$$k = \frac{\omega}{a} \qquad (10)$$

Where:

ω = angular frequency

a = sound velocity

18. From equation (8) to (10) we will get k = 2.68, L_s = 81.85mm, x_s = 81.85mm. from here we could get the distance of hot end stack to the driver is $x_s - L_s/2 = 40.925$

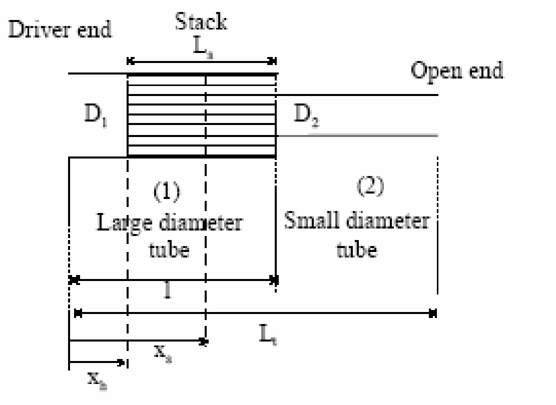


Figure 2.6: An optimized λ/4 resonator like been suggest by Hofler

19. The dimensionless cooling power and dimensionless acoustics power are:

$$Q_{cn} = -\frac{\delta_{kn} D^2 \sin(2x_n)}{8\gamma(1+\sigma)} x \left(\frac{\Delta T_{mn} \tan(x_n)}{(\lambda - 1) B L_{sn}} \frac{1+\sqrt{\sigma}+\sigma}{1+\sqrt{\sigma}} - \left(1+\sqrt{\sigma} - \sqrt{\sigma}\delta_{kn}\right) \right)$$

……….. (11)

$$W_n = \frac{\delta_{kn} L_{sn} D^2}{4\gamma} (\gamma - 1) B \cos(x_n) x \left(\frac{\Delta T_{mn} \tan(x_n)}{B L_{sn} (\gamma - 1)(1+\sqrt{\sigma})\Lambda} \right) - \left(\frac{\delta_{kn} L_{sn} D^2}{4\gamma} \frac{\sqrt{\sigma} \sin(x_n)}{B\Lambda} \right)$$

………..(12)

NOTE: The entire trigonometry functions are in radian not in degree

Where:

D = Drive ratio

x_n = Normalized center position

γ = Ratio of isobaric to isochoric specific heats

σ (Pr) = Prandtl Number

ΔT_{mn} = Normalized Temperature difference

B = Blockage ratio or porosity

L_{sn} = Normalized stack length

δ_{kn} = Normalized thermal penetration depth

While the δ_{kn} and Λ are given by

$\delta_{kn} = \delta_k / y_o$ Where y_o = half plate spacing

$$\Lambda = 1 - \sqrt{\sigma}\delta_{kn} + \frac{1}{2}\sigma\delta_{kn}^2 \qquad (13)$$

20. Under these conditions the dimensionless (normalized) cooling power is Q_{cn} = 3.69 x10^{-6}. The relations between dimensionless cooling power with cooling power and dimensionless acoustics power with acoustics power are:

$$Q_{cn} = \dot{Q}_c / p_m a A \qquad (14)$$

$$W_n = \dot{W} / p_m a A \qquad (15)$$

Where:

Q_{cn} = Dimensionless / Normalized cooling power

$\dot{Q}_{cn}$ = cooling power

p_m = Average Pressure

a = sound velocity

A = Stack cross sectional area

W_n = Dimensionless / Normalized acoustic power

$\dot{W}_n$ = Acoustic Power

21. From equations (14) we will get A = 1.45x10^{-3} m^2 = 14.5 cm^2. Thus, the equivalent radius of the stack is about r = 2.15cm

Table 2.3 : List of stack parameters

Stack Parameter
Thermal Conductivity : $K_s = 0.16$ W/m.K
Heat capacity : $c_s = 1100$J/kg.K
Blockage Ratio or Porosity : B = 0.75
Density: $\rho_s = 1400$ kg/m^3
Stack plate spacing : $2y_o = 0.3$mm
Stack plate thickness: $2l = 0.1$mm
Stack radius : r = 2.15cm
Stack center : $x_s = 81.85$mm
Stack length : $L_s = 81.85$mm

RESONATOR DESIGN

22. After all the stack parameter has been decided, we then calculate the resonator parameter.

    First of all we decide whether to use a λ/4 or λ/2 length resonator. Many researchers suggested using the λ/4 because λ/4-resonator will dissipate only half the energy dissipated by a λ/2-resonator.

23. Hofler showed that λ/4 resonators can be further optimized by reducing the diameter of the resonator part on the right of the stack. The losses in part (2) are plotted as a function of the ratio D_2/D_1 in Figure 2.7.

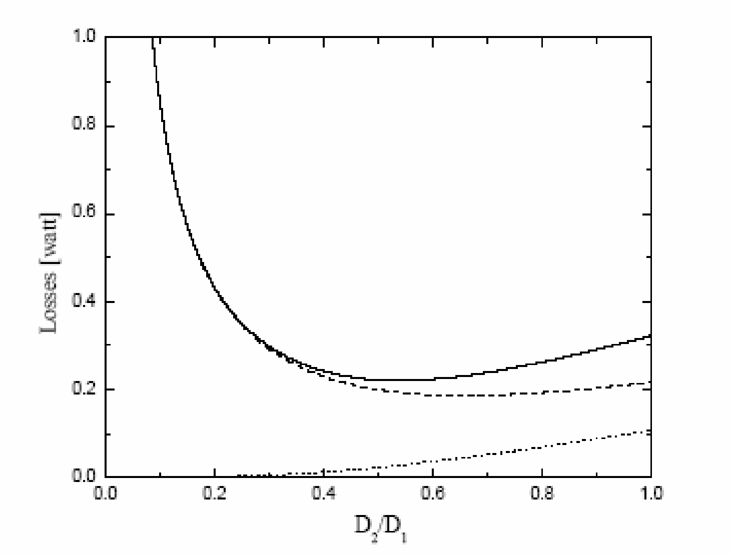


Figure 2.7: The calculated losses in the small diameter resonator part (2) as a function of the ratio of the diameter of the small diameter tube, D_2 to the diameter of the stack resonator, D_1. The dots are the thermal losses, the dashed-line is the viscous losses and the solid plot represents the total loss. The total loss show minimum at $D_2/D_1 = 0.54$

24. From figure 2.7 we can get $D_2 = 1.161$cm.
25. Using the simplified equation proposed by Tijani's, we can determine the total length of the resonator. (Refer Figure 2.6). Below is the equation proposed by Tijani's

$$\cot(kl) = \left(\frac{D_1}{D_2}\right)^2 \tan(k(L_t - l)) \qquad (16$$

Where:

k = Wave number

l = Length of the large diameter tube

D_1 = Diameter of large tube (stack side)

D_2 = Diameter of small tube

L_t = Total length of resonator

Note:

a. **There are two *l*'s here, length of the large diameter tube in resonator design and length of half stack plate thickness in stack design.**
b. **The Trigonometric function is in degree not in radian.**

26. From here onwards we have made our own approach in designing the small resonator diameter. Refer to appendix.
27. To make sure that there will be no leaking between the resonator parts, we design a groove to put 'O' ring as can be seen in the appendix.
28. Since there is no information on the buffer in the literature so far, we designed it base on Tijani's design with some modifications.
29. The end cap is a part to make sure that the resonator is closed so that the pressure will be maintained and there should not be pressure losses. The end cap was also designed to deliver gases from here. And last but not least, the end cap also functions as an open end to the resonator.

HEAT EXCHANGER DESIGN

30. Heat exchangers are necessary to transfer the heat of the thermoacoustics cooling process. Although the design of heat exchanger is a critical task, there is still little known about the heat transfer in oscillatory flow with zero mean velocity.

a) Cold Heat exchanger

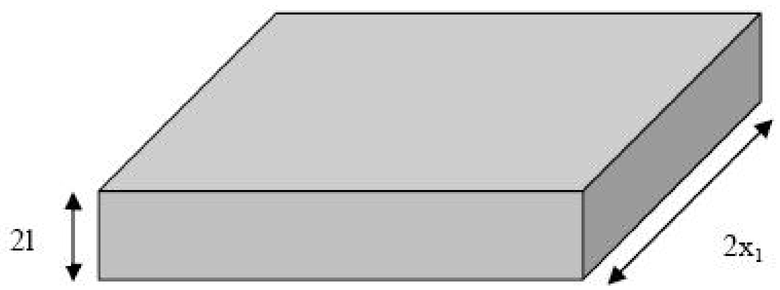


Figure 2.8: Cold heat exchanger parameters

31. The optimum length corresponds to the peak to peak displacement of the gas at the cold heat exchanger location. The displacement amplitude is given by

$$x_1 = \frac{p_o}{\omega \rho_m a} \sin(kx) \qquad (17)$$

Where:

p_o = Dynamic Pressure

ω = angular frequency

ρ_m = Gas density

a = sound velocity

k = Wave Number

32. From the above calculation we know that x = l = 12.27cm, will give x_1= 1.47mm. The optimum length of the cold heat exchanger is thus about $2x_1$= 2.95mm.
33. From the stack design we knows that $2y_o$ = 0.3mm and *2l* = 0.1mm. Refer to Figure 2.3, 2.8 and 2.9 to understand the heat exchanger parameters.

b) Hot Heat exchanger

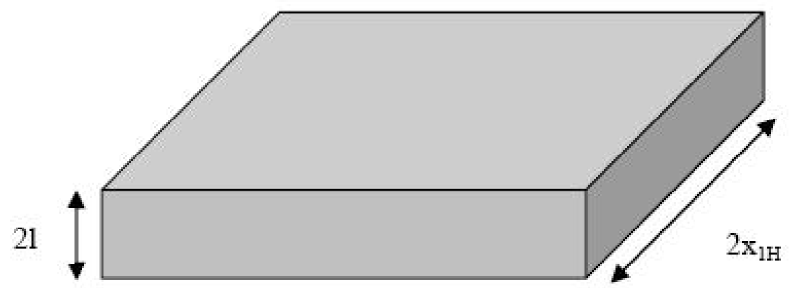


Figure 2.9: Hot heat exchanger parameters

34. The hot heat exchanger is necessary to remove the heat pumped by the stack and to reject it to the circulating cooling water. The optimal length of the heat exchanger is equal to the peak to peak displacement amplitude of the gas at the

heat exchanger. But since the hot heat exchanger should be twice the heat supplied by the cold heat exchanger, the length of the hot heat exchanger should be twice the cold heat exchanger. So $2x_{1H}$= 5.9mm for the hot heat exchanger while the other parameter still the same with the cold heat exchanger.

35. The other parameter like $2y_o$ and *2l* follow the stack and also same with the cold heat exchanger.

CHAPTER 3 - EXPERIMENTAL SET-UP

A thermoacoustic resonator first fabricated under Vot 71891 (Figure 3.1) is used to determine optimized performance conditions for the design, fabrication and later testing of the new thermoacoustic system with this research.

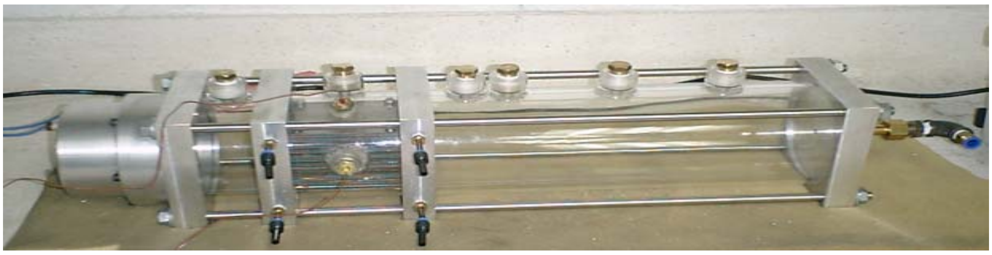


Figure 3.1: Thermoacoustic resonator Vot 71891

The thermoacoustic resonator is first tested for constancy and reliability in generating the thermoacoustic effects in the laboratory and at selected sites.

3.1 Experimental Procedure

Objective: To study the cooling effect from the thermoacoustics heat engine

Equipments: Heat engines thermoacoustics, function generator (LEADER), Power amplifier 2706, Oscilloscope, water recycling system, Scanning data logger thermocouple (Cole Parmer), Thermocouples, water recycling system, water tube, gases and its systems

Procedures: With all the devices arranged as follow;

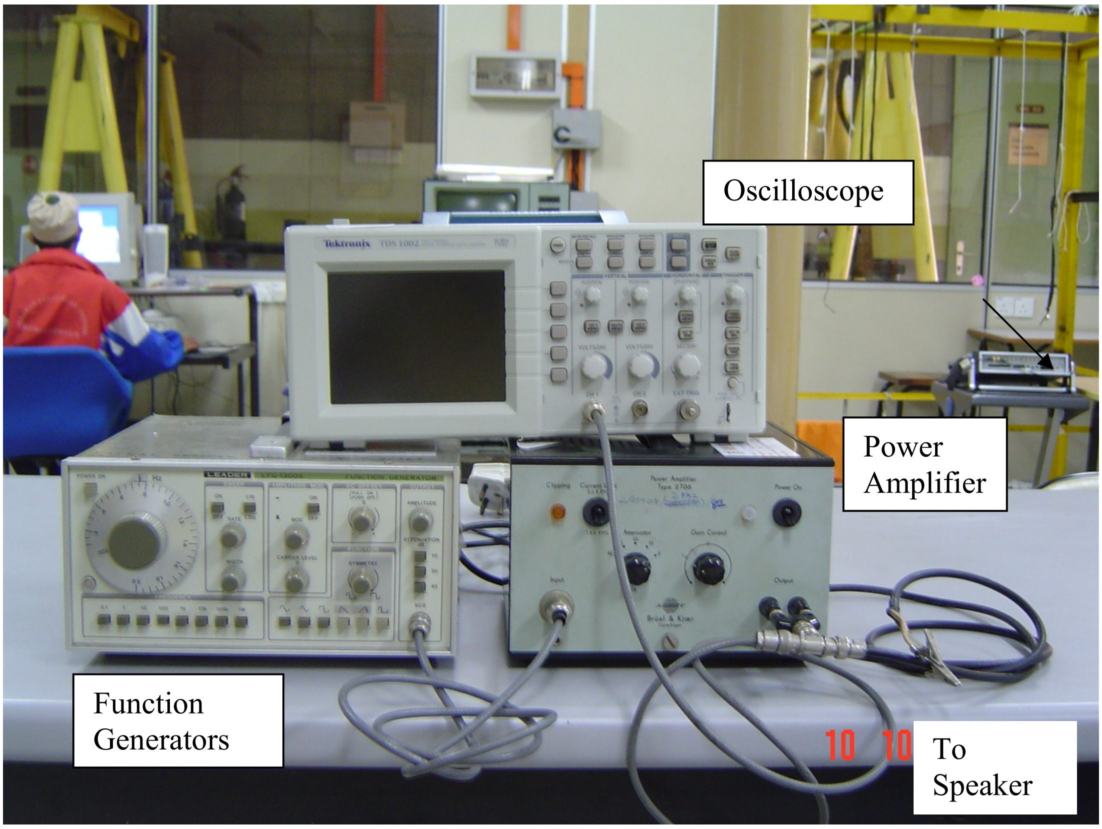


Figure 3.2: Equipments arrangement


(3.2a) **(3.2b)**

Figure 3.2: (3.2a) Function Generators (LEADER) and (3.2b) Power Amplifier

Figure 3.3: Oscilloscope

1. Record the surrounding temperature and pressure and also the temperature of the pipe water.
2. Deliver Helium gas to the resonator.

   NOTE: Make sure that the resonator valve is closed before delivering gas into it. Then set the pressure to 2 bar by referring to the pressure gauge at the helium gas tank. After the pressure is stable, open the resonator valve. Wait until the pressure in the resonator is stable. (It is recommended to have a pressure gauge at the middle of the resonator) Open the resonator valve during this experiment. (Refer to Figure 3.4 & 3.5)

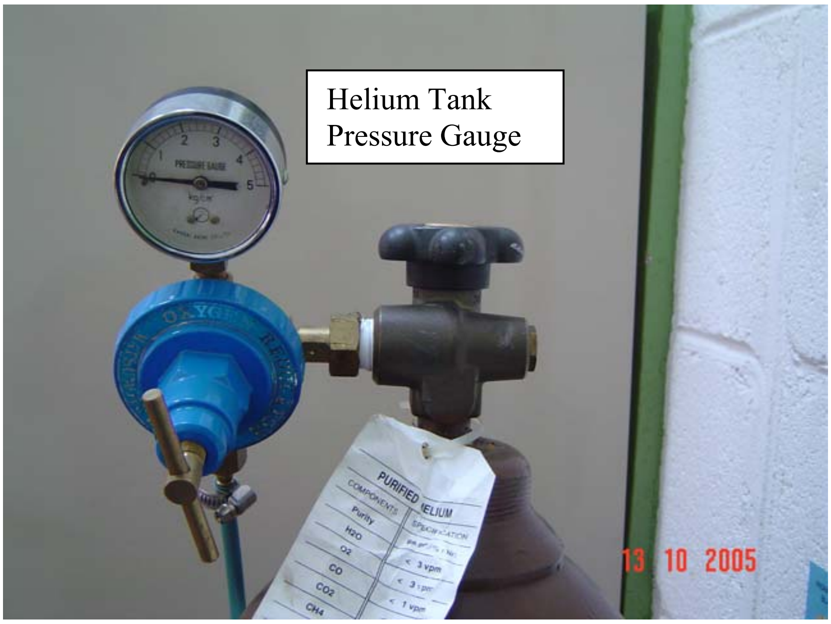


Figure 3.4: Pressure Gauge at the Helium gas tank

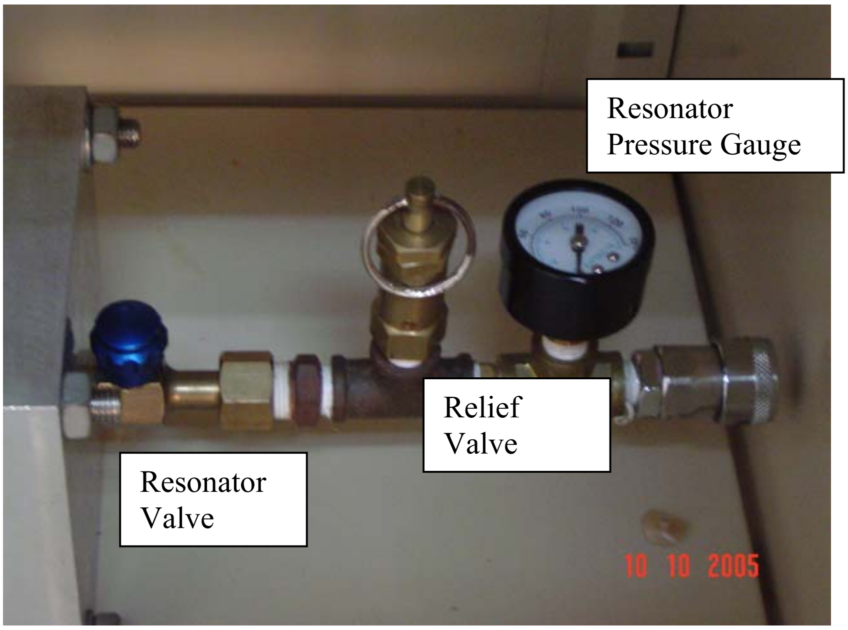


Figure 3.5: Resonator gas inlet system

3. Connect the water recycling system to the hot heat transfer and pipe water to the cold heat transfer.
4. Connect thermocouple T_{A1}, T_{B1}, T_{A2}, T_{B2}, T_S to the Scanning data logger thermocouple. Set data log time to 15 second.

T_{A1} = Temperature at the hot heat exchanger

T_{B1} = Temperature at the cold heat exchanger

T_{A2} = Temperature at the hot heat exchanger

T_{B2} = Temperature at the cold heat exchanger

T_S = Surrounding Temperature (room temperature)

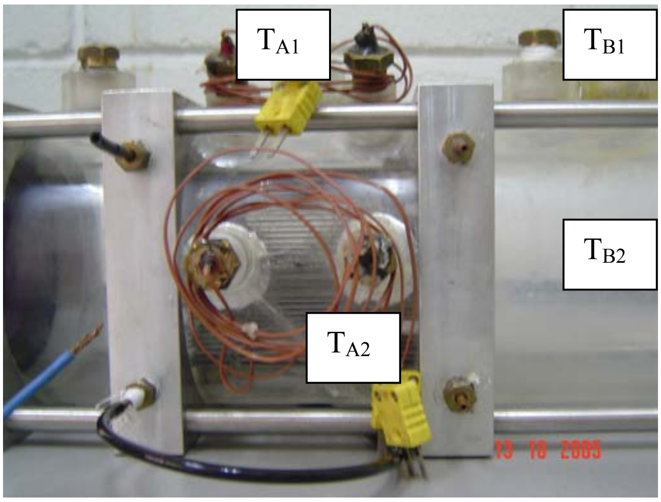


Figure 3.6: Hot and cold heat exchanger

5. When all of the settings are ready, switch on the water pump (for the heat hot exchanger).
6. Switch on the Function Generator altogether with the Power amplifier and set the frequency to 1000Hz. You will see the 'clipping' light will be on. Set the gain of the amplifier to a reasonable value.
7. Record data using "scanlog"program.
8. Switch on the speaker for two hours.
9. While this experiment is running, make sure to check the pressure and temperature from time to time.
10. After two hours, switch off the speaker, and continue this experiment for 5 hours more.
11. Set to the desired time for every data.
12. Record the data.
13. Set to the desired frequency on the Function Generator.
14. On the speaker for a time that should been set in this experiment. (for example two hours).
15. Then turn the speaker off to compare the cooling effect between when the speaker was on and the speaker was off.

CHAPTER 4 - RESULTS AND DISCUSSION

4.1 Result

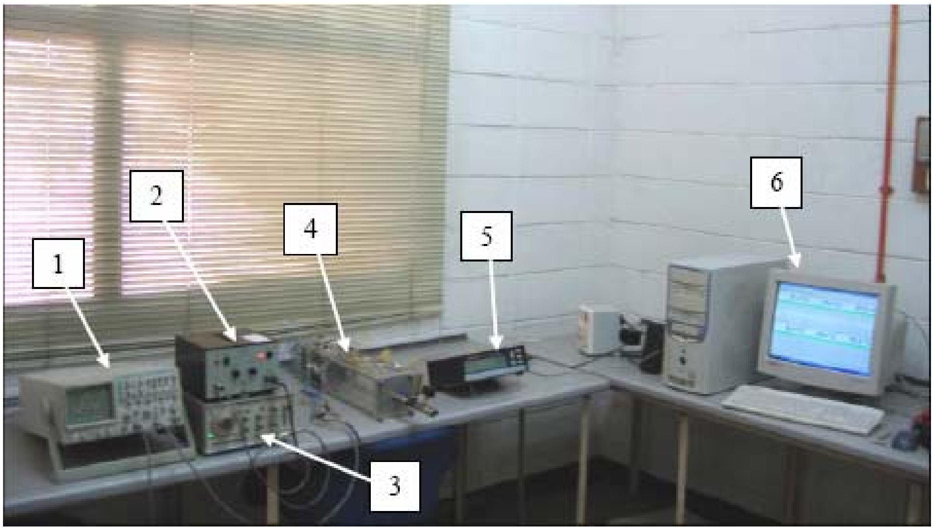
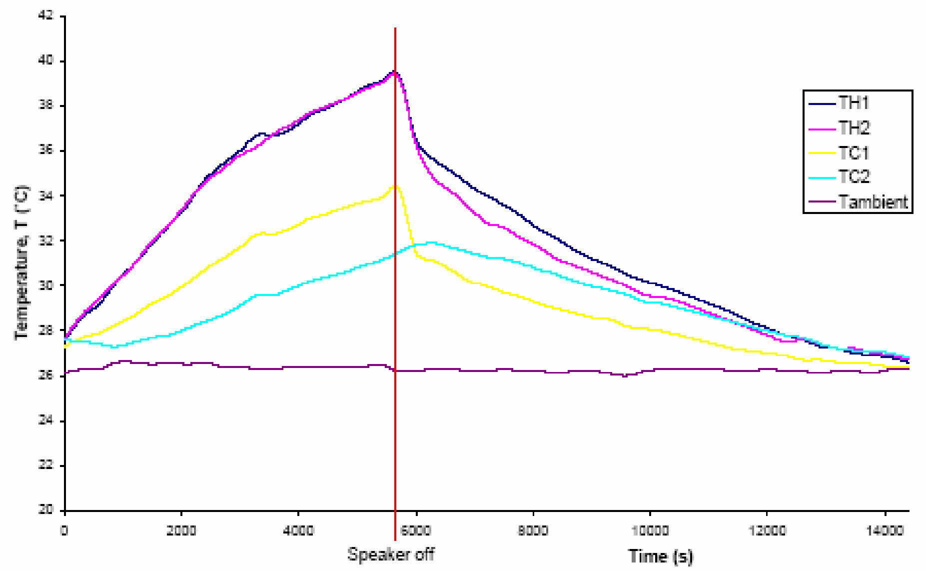
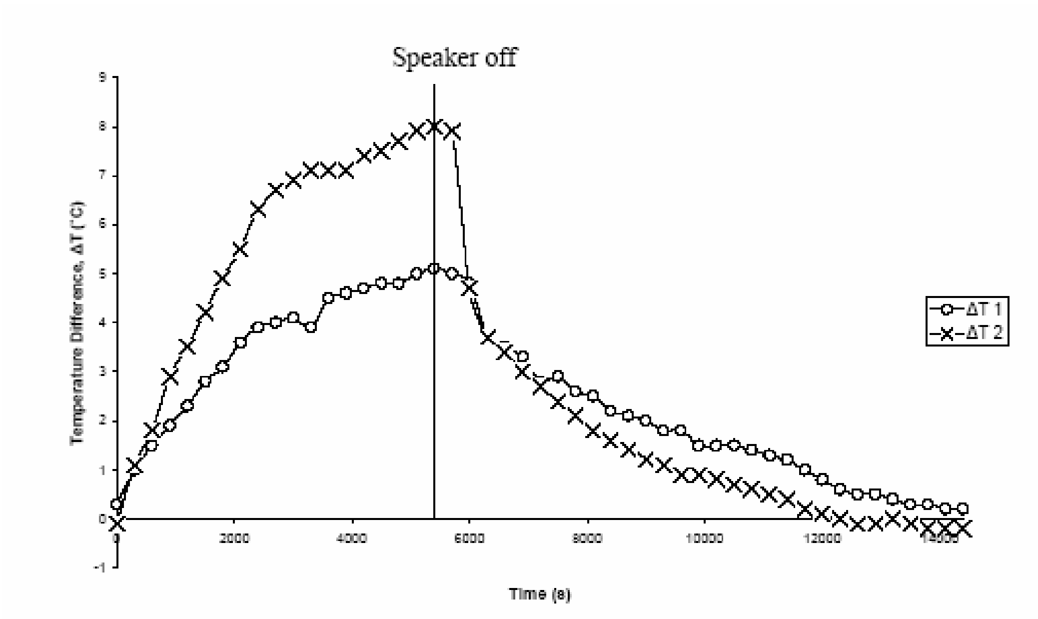


Figure 4.1: Testing set up in laboratory. (1) Kenwood Digital Storage Oscilloscope DCS – 7020, (2) Bruel & Kjaer Power Amplifier Type 2706, (3) Leader Function Generator LFG-1300 S, (4) Resonator, (5) Cole Parmer Scanning Thermometer, (6) Computer as data recording system.



Graph 4.1: Temperature vs. Time for testing in Laboratory working at 500 Hz with 40% gain



Graph 4.2: Temperature Difference vs. Time for testing in Laboratory working at 500 Hz with 40% gain

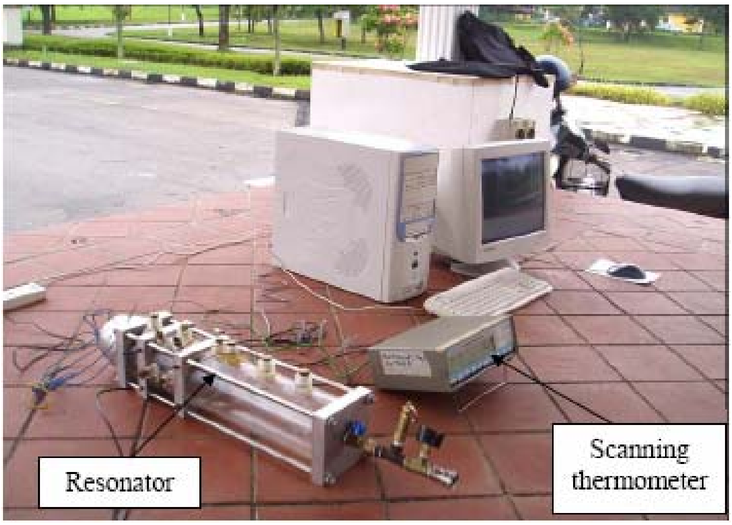
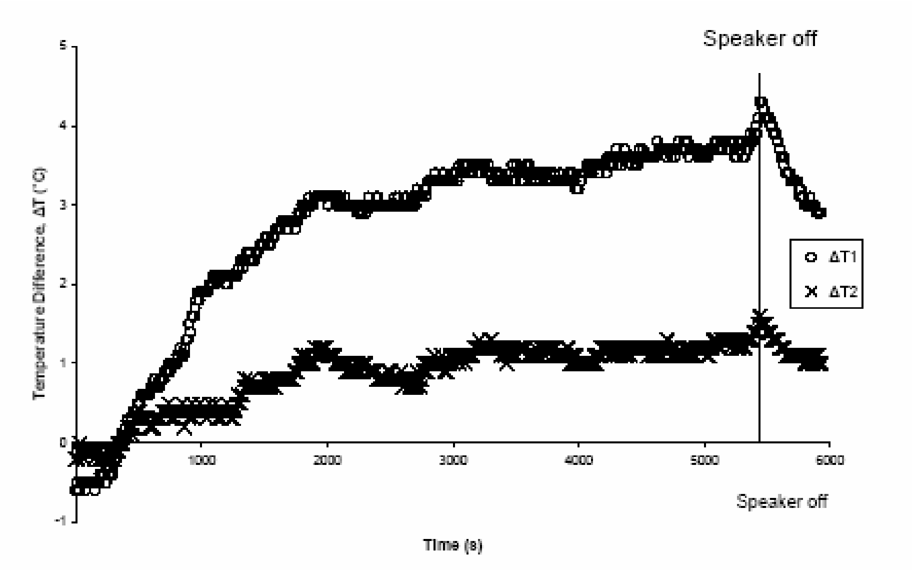
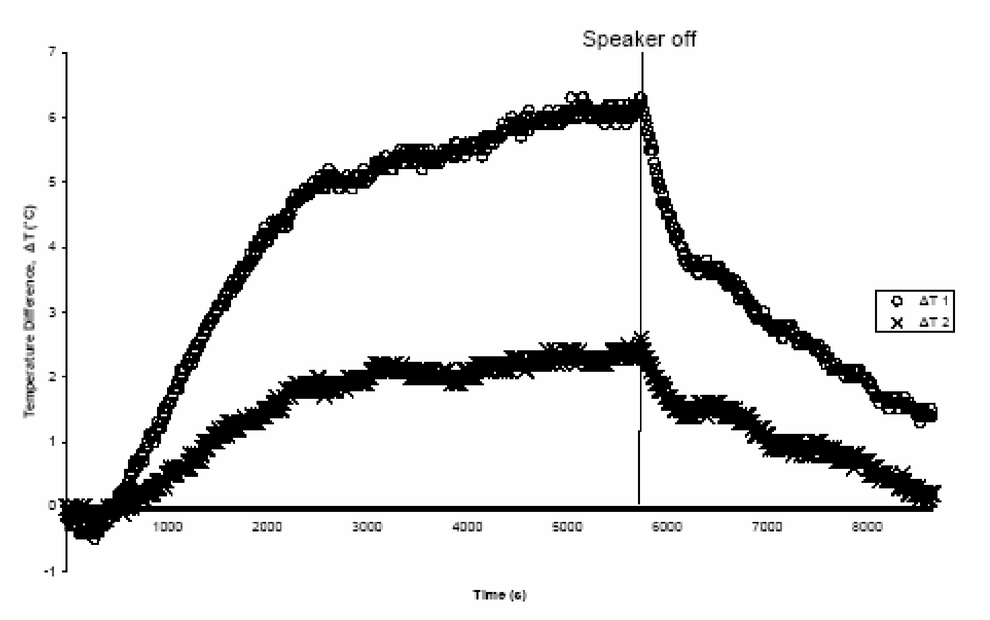


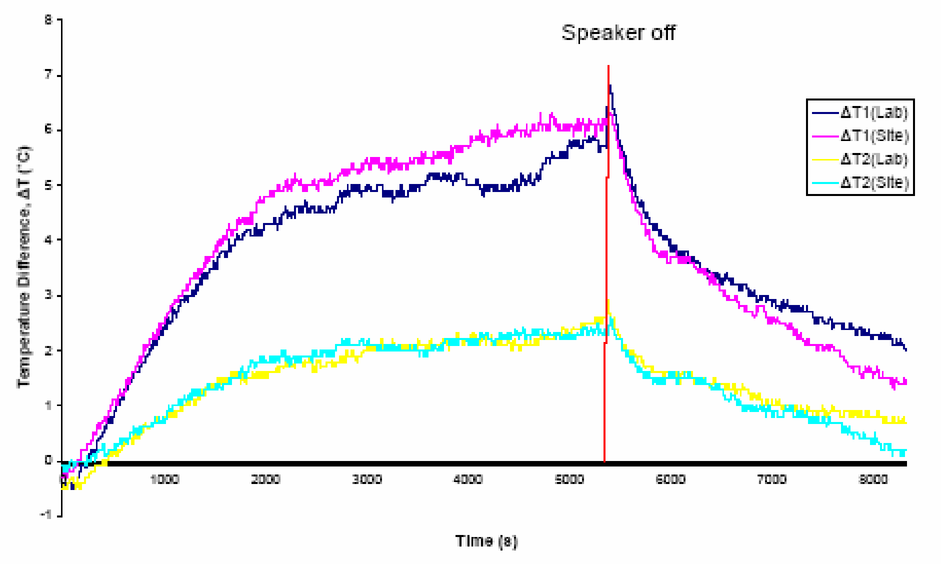
Figure 4.2: Site Testing at Padang Kawad



Graph 4.3: Temperature Difference vs. Time for testing at Padang Kawad working at 500 Hz with 20% gain



Graph 4.4: Temperature Difference vs. Time for testing at Padang Kawad working at 500 Hz with 40% gain



Graph 4.5: Comparison of Temperature difference vs Time between laboratory and site testing at 350 Hz with 40 % gain

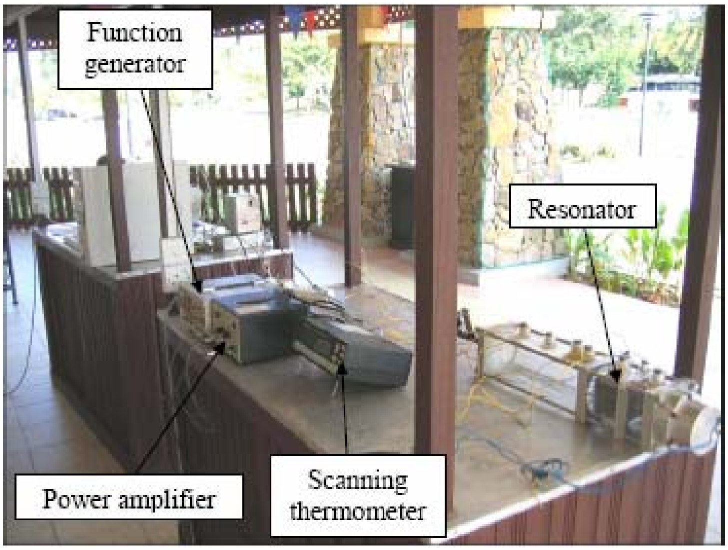
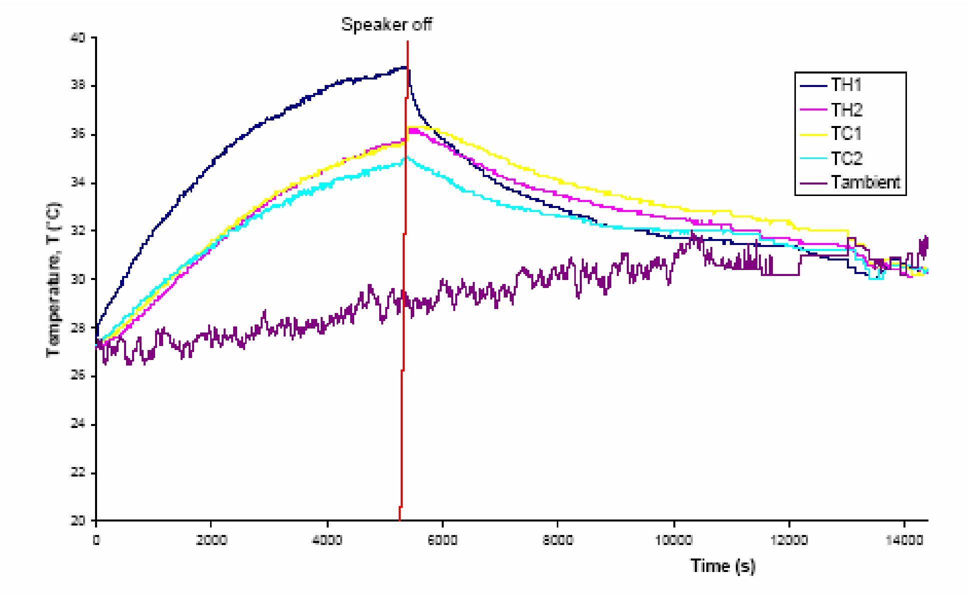
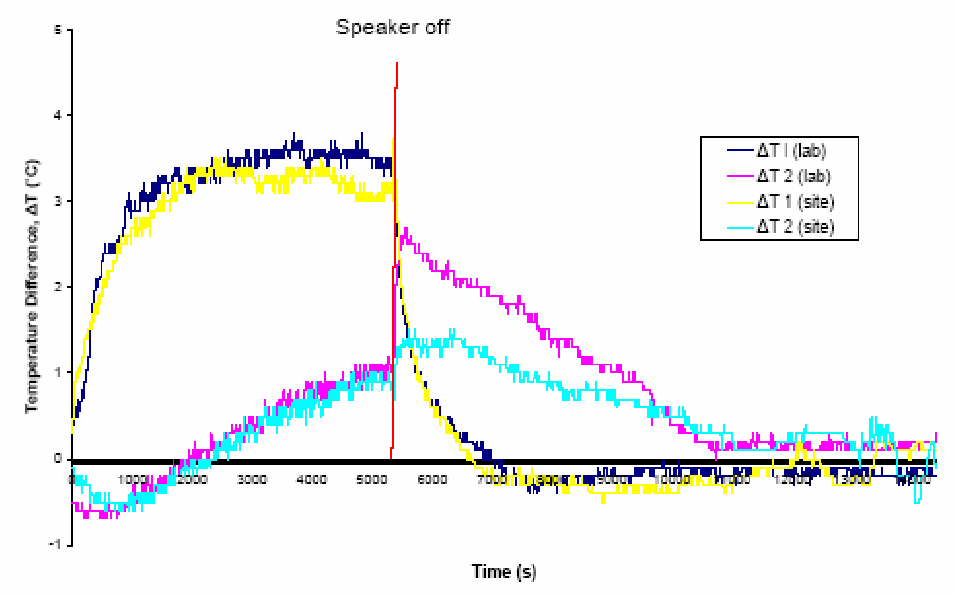


Figure 4.3: Site Testing at Rumah Alumni



Graph 4.6: Temperature Difference vs. Time for testing at Rumah Alumni working at 200 Hz with 40% gain



Graph 4.7: Comparison of Temperature difference vs Time between laboratory and site testing at 200 Hz with 40 % gain

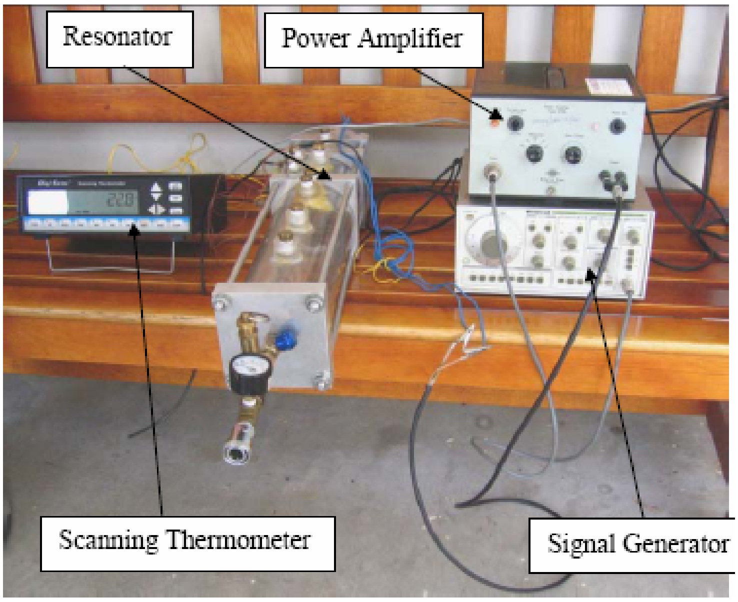
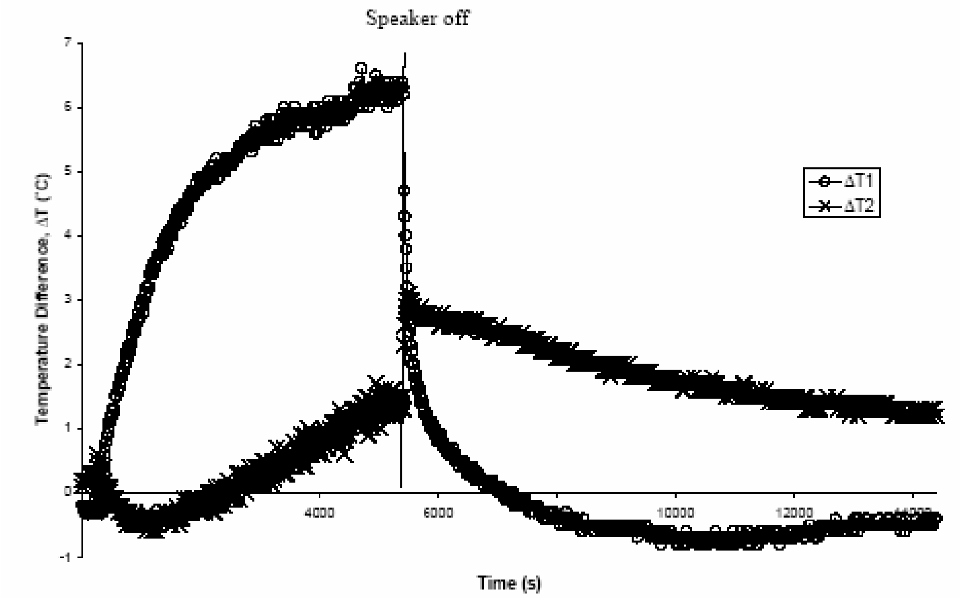
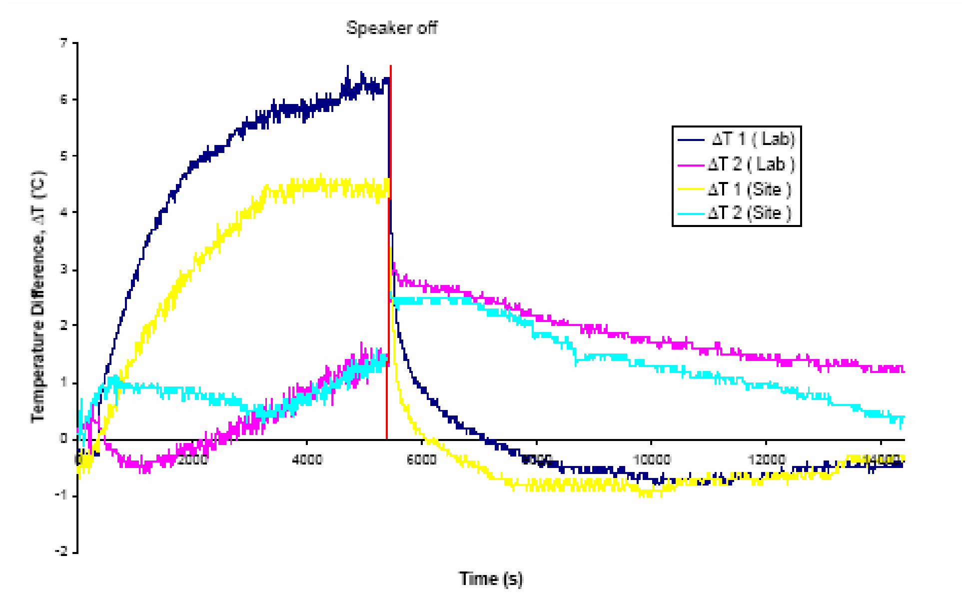


Figure 4.4: Site testing at ground floor of C24, FKM



Graph 4.9: Temperature Difference vs. Time for testing at ground floor, C24 working at 100 Hz with 40% gain



Graph 4.10: Comparison of Temperature difference vs. Time between laboratory and site testing at 100 Hz with 40 % gain

1. From graph 4.11, we can see that the temperature slightly rose.
2. From graph 4.2, the ΔT_2 increased faster than ΔT_1.
3. But for graph 4.3 and 4.4, ΔT_1 increased faster than ΔT_2.
4. When we compare the result from site testing 1 (Padang kawad) and at laboratory (Graph 4.5) we can see there is insignificant. The small difference between these results may cause from the surrounding effect such as weather and humidity.
5. For site testing 2 (Rumah alumni as we can see from graph 4.6) the graph have a similar pattern if to be compared to the testing at the laboratory with the same testing parameter. This similarity can be seen at the graph 4.7.
6. For site testing 3 (ground floor C24) graphs 4.8 and 4.9, we can say that there is a little different of pattern between tread lines for ground floor C24 to the test at laboratory. This happen by the effect of surrounding. At the ground floor of C24, there were moving air and unstable heat from surrounding.

CHAPTER 5 - CONCLUSION

Conclusions and suggestions

Here we can conclude that, there were thermoacoustics effects generated by the old thermoacoustics system. This can be seen in the graphs above, using the same operating parameters but with different gain, different results were seen. Even though the temperature increased and not decreased as expected, the design was not optimized in this old system. The new thermoacoustic system was completed based on these experiments. A few experiments had been completed with a temperature drop of 1 degree obtained even though the design was for a 35 degree temperature drop. Issues like heat interactions between the system and the surroundings, thicker stack plate used (due to difficulties in fabricating thinner optimized ones), very small water pump needed and fine-tuning of other operating parameters need to be addressed. Unfortunately, the project contract has ended and these issues could not be resolved. It is hoped that with new funding, further experiments can be conducted to improve the current system, in particular the stack and heat exchanger parts where the heat interactions are crucial for the success of this system and future ones.

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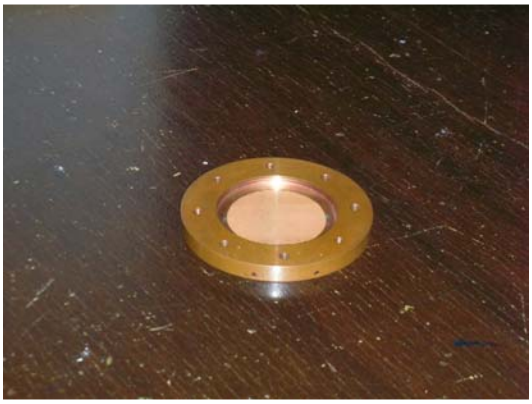
APPENDIX

The Fabricated Thermoacoustic Refrigeration System

End Cap, Buffer and Small Diameter Resonator

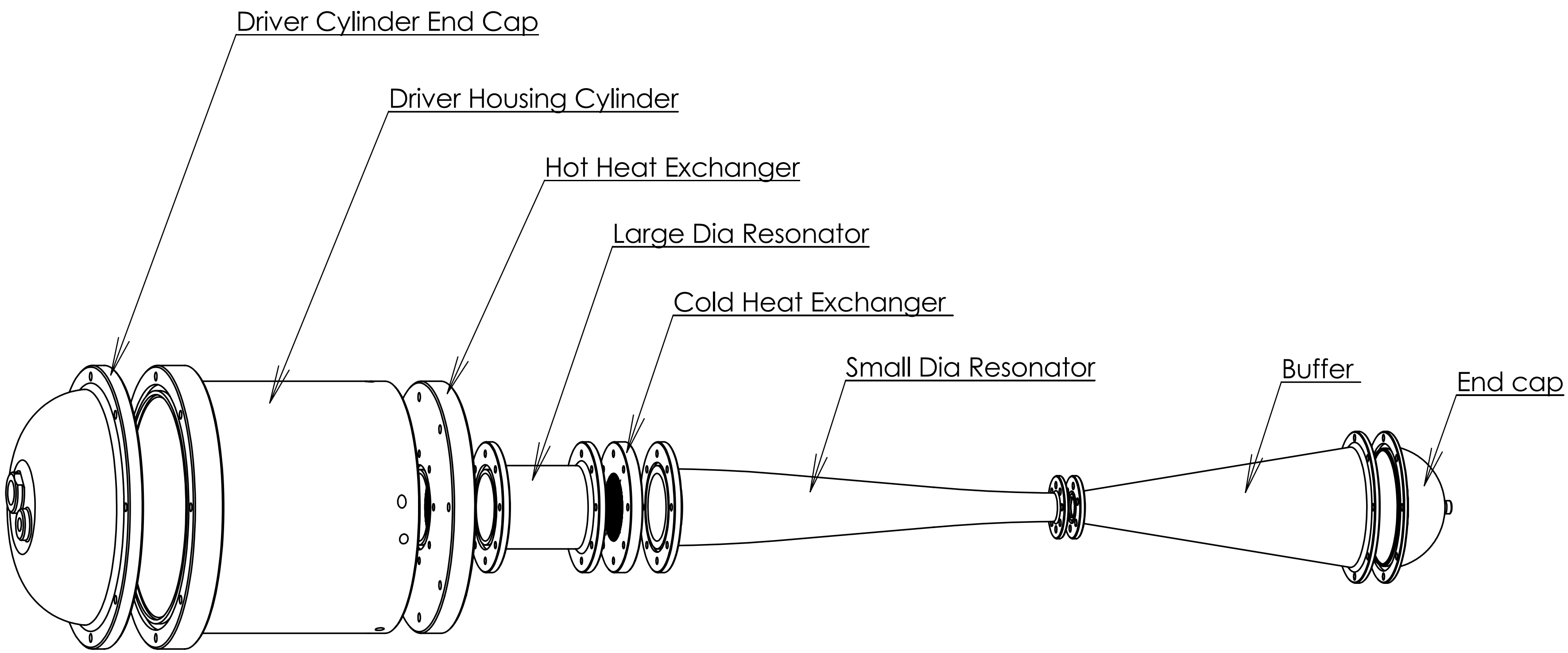
Stack and Stack Holder

Driver Housing, Driver Cap, Large Diameter Resonator Hot Heat Exchanger



Cold Heat Exchanger

Note: All bore holes in the drawings follows normal tool bit



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APPV'D	DR. NORMAH					
MFG						
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End of Project Report Guidelines

A. Purpose

The purpose of the End of Project is to allow the IRPA Panels and their supporting group of experts to assess the results of research projects and the technology transfer actions to be taken.

B. Information Required

The following Information is required in the End of Project Report :

- Project summary for the Annual MPKSN Report;
- Extent of achievement of the original project objectives;
- Technology transfer and commercialisation approach;
- Benefits of the project, particularly project outputs and organisational outcomes; and
- Assessment of the project team, research approach, project schedule and project costs.

C. Responsibility

The End of Project Report should be completed by the Project Leader of the IRPA-funded project.

D. Timing

The End of Project Report should be submitted within three months of the completion of the research project.

E. Submission Procedure

One copy of the End of Project is to be mailed to :

IRPA Secretariat
Ministry of Science, Technology and the Environment
14th Floor, Wisma Sime Darby
Jalan Raja Laut
55662 Kuala Lumpur

End of Project Report

A. Project number : 08-03-08-0006

Project title : Environmental Friendly Refrigeration with Thermoacoustics

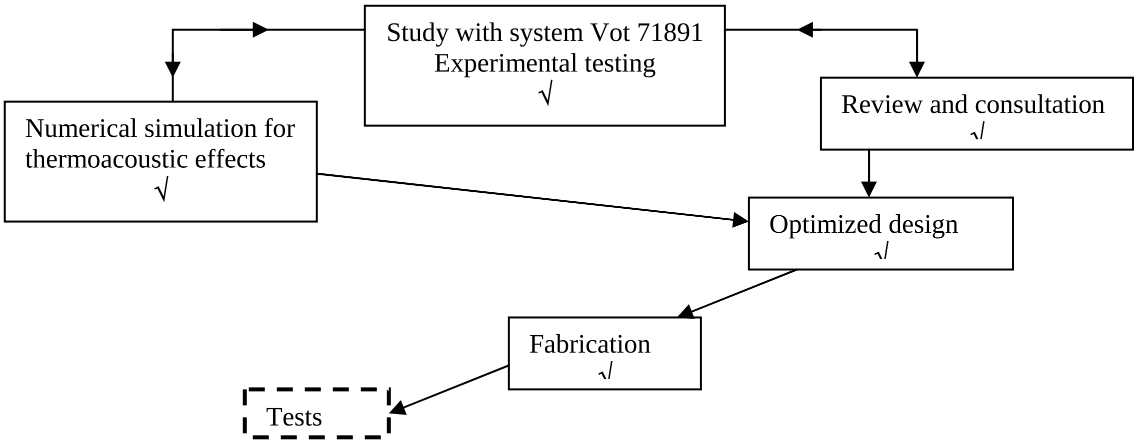
Project leader: Dr Normah bt Mohd Ghazali

Tel: 07-5534577 Fax: 07-5566159

B. **Summary for the MPKSN Report (**for publication in the Annual MPKSN Report, please summarise the project objectives, significant results achieved, research approach and team structure)

The project objectives were (i) to study further the development of the acoustic waves from waste heat, and (ii) to develop application for refrigeration system from the acoustic waves generated from (i). Since thermoacoustic is a new field even with respect to the rest of the world, much of the fundamentals behind its operation is still unexplained. The project objectives were not fully realised within the time frame of 3 years due to unavailable references, lack of fabrication technology, and scepticism among potential researchers. Two of the initial researchers left for further studies after 1 year the project started. The group managed direct consultation via e-mails with the pioneer of thermoacoustics, Dr. Greg Swift of the Los Alamos National Laboratory, USA. Thermoacoustic effects involve heat exchanging process between solid boundaries and oscillating fluid. Handbook data for today's heat exchangers are for steady flow, while thermoacoustic experiments involve oscillating flow. To date, the design of heat exchangers for thermoacoustic devices is a process of compromising among many worthy goals: high heat transfer on the thermoacoustic side, low acoustic power dissipation on the acoustic side, small temperature difference within the metal barrier between thermoacoustic fluid and cooling water, high heat transfer coefficient on the cooling water side, low pressure drop on the cooling water side, low cost, and low risk (Ref: Thermoacoustic: A Unifying Perspective for Some Engines & Refrigerators, Greg Swift, Los Alamos National Laboratory, 2001).

This research fully utilized a system developed under a previous research, Vot 71891 to generate a better understanding in the design and fabrication of the current system.



Numerical simulation was successfully completed identifyingan optimized mixture of rare gases. A series of tests for constancy and reliability were done both inside the laboratory and at selected sites with pure Helium. Unfortunately, even with a complete CAD design, after much efforts searching for a company to fabricate the system designed within a limited budget and time, the identified company failed to deliver the first time around. Subsequent discussions were made before the system was finally completed in February 2006, 1 month before the project officially ended. This system performed similarly as the system made under Vot 71891 under similar operating conditions. This system was fabricated to accommodate pressure up to 10 bar for an optimized performance but time and budget constraints did not permit experiments under this latter conditions.

C. Objectives achievement

- **Original project objectives** (Please state the specific project objectives as described in Section ll of the Application Form)
  1. To study further the development of the acoustic waves from waste heat.
  2. To develop application for refrigeration system from the acoustic waves generated from (1).

- **Objectives Achieved** (Please state the extent to which the project objectives were achieved)
  The range of temperature from waste heat produced by a portable combustion unit was identified and if water is used as the working fluid, constancy in flow rate and temperature was confirmed for palm oil kernels, rice husks pellets, wood, and wood briquettes.
  A refrigeration system was completed but the heat engine was not. The completed system runs on electricity and designed to also run on a 10 – 12 Volt battery. It may be made portable if the electrical side can be addressed.

- **Objectives not achieved** (Please identify the objectives that were not achieved and give reasons)

1. The heat engine that can generate acoustics from waste heat was not fabricated. Further review, feasibility studies, and consultation found that the system is not optimized or economical and thus has no potential for prototyping.
2. There was an absence of any references locally (all have been brought back from PhD study and Singapore Universities) in addition to limited budget and no company that can make the supposedly simple refrigeration system. Thus acoustics for cooling effects were produced using a borrowed signal generator and amplifier.

D. **Technology Transfer/Commercialisation Approach** (Please describe the approach planned to transfer/commercialise the results of the project)

- Much knowledge has been gained through this funding and direct communication with Greg Swift.
- One master student is now an academia at Curtin University, Sarawak Branch, and another at UiTM Shah Alam. Collaboration with the former is ongoing to look into the fundamental aspect of the shock waves in the design our applications for fundamental research grant, and harnessing cooling effects in the upcoming science fund.
- If the heat transfer problems can be overcome, and cooling effects registered, then we may have a thermoacoustic refrigeration without CFCs nor a compressor. Commercialization will not be possible until a prototype can be made public and the system performance can be exhibited.

E. Benefits of the Project (Please identify the actual benefits arising from the project as defined in Section lll of the Application Form. For examples of outputs, organisational outcomes and sectoral/national impacts, please refer to Section lll of the Guidelines for the Application of R&D Funding under IRPA)

- **Outputs of the project and potential beneficiaries** (Please describe as specifically as possible the outputs achieved and provide an assessment of their significance to users)

Since the system which was fabricated for operation under 10 bar was not tested under that condition, cooling was not observed. If this issue can be addressed, a refrigeration system may be proved yet with thermoacoustics and potential for a viable alternative to the current vapor-compression system and environmentally friendly. There is a definite demand for a portable refrigeration system that can provide cooling at will.

- **Organisational Outcomes** (Please describe as specifically as possible the organisational benefits arising from the project and provide an assessment of their significance)

The research has created a specialized field at UTM in particular, and the research has recruited academia (Curtin University, Sarawak branch, and UiTM) and engineers who are aware of the potentials in what the Time Magazine in the 2004 issue called "the greatest fluid power" of the 21st century. This is significant considering that the field is new and the starting point was at zero knowledge and awareness in Malaysia.

- **National Impacts** (If known at this point in time, please describes specifically as possible the potential sectoral/national benefits arising from the project and provide an assessment of their significance)

F. Assessment of project structure

- **Project Team** (Please provide an assessment of how the project team performed and highlight any significant departures from plan in either structure or actual man-days utilised)

- Two of the researchers have left for further studies after a year and one more has been promoted to the second academic highest position at the faculty. The outcome was not favorable to the development of the project within the time given.
- A research officer trained for 1 year left because of family pressure for a more secured. Training in time, funds, and energy were wasted as the person left for unrelated job option.
- Project leader had to put extra efforts into the project but due to the brain drain, progress and growth is slow.

- **Collaborations** (Please describe the nature of collaborations with other research organisations and/or industry)

Potential collaboration for future and further studies into thermoacoustics has started with applications for research grants under RMK9.

G. Assessment of Research Approach (Please highlight the main steps actually performed and indicate any major departure from the planned approach or any major difficulty encountered)

- A review was made as planned. Discovery of optimized design and the reality of inadequate consultation, absence of references locally, reduced manpower, and the greatest obstacle of all – budget/technology constraint – has forced a departure from the original structure of research work planned (Part V original application). Field tests managed to be completed with a previous system and numerical works were completed as scheduled.

H. Assessment of the Project Schedule (Please make any relevant comment regarding the actual duration of the project and highlight any significant variation from plan)

- The actual duration of the project would not have been enough if both the heat engine and reversed heat engine were to be designed, fabricated, and tested because of the lack of references, consultation, budget and technology know-how.
- The final system would have been able to be site tested if the company which undertook the fabrication job did not botch the fabrication the first time around and the researcher trained had not left after 1 year of training.

I. **Assessment of Project Costs** (Please comment on the appropriateness of the original budget and highlight any major departure from the planned budget)

- The original budget approved did not include external consultation as planned in the original application and thus consultation was only done through the e-mails. This is not as encouraging as and conducive to research as a face-to-face consultation.
- Budget requested for fabrication and equipments was not adequate due to the project leader's inexperience with the Malaysian background in the lack of companies capable of precision engineering and expensive fabrication costs. Thus many parts of the system design and fabrication had to be compromised.
- There was left over budget for contract staffs. The leader was trying to recruit locals but local graduates are interested only in high salary and secured posts. Lack of commitment had resulted in wasted training and no candidates for the graduate studies planned in the application form.

J. **Additional Project Funding Obtained** (In case of involvement of other funding sources, please indicate the source and total funding provided)

K. **Other Remarks** (Please include any other comment which you feel is relevant for the evaluation of this project)

Please take note that thermoacoustic for useful purposes is a new field throughout the world. Commitment and lack of support system at acceptable price in Malaysia are the main obstacles to developing this new field. Intellectual capacity can and has been developed and expanded with this funding within the time frame and this cannot be measured quantitatively. It is hoped that the research can be continued to realized an environmentally refrigeration system for special applications and at the same time look into theless-understood phenomena of thermoacoustic effects in closed chambers.

Date : **Signature :**

Benefits Report Guidelines

A. Purpose

The purpose of the Benefits Report is to allow the IRPA Panels and their supporting experts to assess the benefits derived from IRPA-funded research projects.

B. Information Required

The Project Leader is required to provide information on the results of the research project, specifically in the following areas:

- Direct outputs of the project;
- Organisational outcomes of the project; and
- Sectoral/national impacts of the project.

C. Responsibility

The Benefits Report should be completed by the Project Leader of the IRPA-funded project.

D. Timing

The Benefits Report is to be completed within three months of notification by the IRPA Secretariat. Only IRPA-funded projects identified by MPKSN are subject to this review. Generally, the Secretariat will notify Project Leaders of selected projects within 18 months of project completion.

E. Submissin Procedure

One copy of this report is to be mailed to :

IRPA Secretariat
Ministry of Science, Technology and the Environment
14th, Floor, Wisma Sime Darby
Jalan Raja Laut
55662 Kuala Lumpur

Benefit Report

1. Description of the Project

A. Project identification

1. Project number : 08 – 03 – 08 - 0006

2. Project title : Environmentally Friendly Refrigeration with Thermoacoustics

3. Project leader : Dr Normah bt Mohd Ghazali

B. Type of research

Indicate the type of research of the project (Please see definitions in the Guidelines for completing the Application Form)

- [ ] Scientific research (fundamental research)
- [x] Technology development (applied research)
- [ ] Product/process development (design and engineering)
- [ ] Social/policy research

C. Objectives of the project

1. Socio-economic objectives

Which socio-economic objectives are adressed by the project? (Please indentify the sector, SEO Category and SEO Group under which the project falls. Refer to the Malaysian R&D Classification System brochure for the SEO Group code)

Sector : Energy, Mineral & Geo-science, 02

SEO Category : Energy Supply, S20500

SEO Group and Code : Conservation and efficiency, S20504

2. Fields of research

Which are the two main FOR Categories, FOR Groups, and FOR Areas of your project? (Please refer to the Malaysia R&D Classification System brochure for the FOR Group Code)

a. Primary field of research

FOR Category : Applied Sciences and Technologies, F10600

FOR Group and Code : Energy Industry, F10606

FOR Area : Other energy industry

b. Secondary field of research

FOR Category : Engineering Sciences, F10700

FOR Group and Code : Mechanical and industrial engineering , F10701

FOR Area : Mechanical engineering

D. **Project duration**

What was the duration of the project ?

36 Months

E. **Project manpower**

How many man-months did the project involve?

94 Man-months

F. **Project costs**

What were the total project expenses of the project?

RM 101,303.80

G. **Project funding**

Which were the funding sources for the project?

Funding sources	Total Allocation (RM)
IRPA	174,000.00
Internal Funds	113,400.00

ll. Direct Outputs of the Project

A. Technical contribution of the project

1. **What was the achieved direct output of the project :**

For scientific (fundamental) research projects?

- [ ] Algorithm
- [ ] Structure
- [ ] Data
- [ ] Other, please specify : ______________________________

For technology development (applied research) projects :

- [ ] Method/technique
- [√] Demonstrator/prototype
- [√] Other, please specify : __Identification of optimized working fluid____________

For product/process development (design and engineering) projects:

- [ ] Product/component
- [ ] Process
- [ ] Software
- [ ] Other, please specify : ______________________________

2. **How would you characterise the quality of this output?**

- [√] Significant breakthrough
- [ ] Major improvement
- [ ] Minor improvement

B. Contribution of the project to knowledge

1. How has the output of the project been documented?

- [√] Detailed project report
- [√] Product/process specification documents
- [√] Other, please specify : __Conference/Journal__________________________

2. Did the project create an intellectual property stock?

- [ ] Patent obtained
- [ ] Patent pending
- [ ] Patent application will be filed
- [ ] Copyright

3. What publications are available?

- [√] Articles (s) in scientific publications — How Many: 3
- [√] Papers(s) delivered at conferences/seminars — How Many: 5
- [ ] Book
- [ ] Other, please specify : ____

4. How significant are citations of the results?

- [ ] Citations in national publications — How Many: ________________
- [ ] Citations in international publications — How Many: ________________
- [√] None yet
- [ ] Not known

lll. Organisational Outcomes of the Project

A. Contribution of the project to expertise development

1. How did the project contribute to expertise?

- [ ] PhD degrees — How Many: ________________
- [√] MSc degrees — How Many: 1
- [√] Research staff with new specialty — How Many: 1
- [√] Other, please specify: __Academia now working at other IPTs and may recruit others

2. How significant is this expertise?

- [√] One of the key areas of priority for Malaysia
- [ ] An important area, but not a priority one

B. Economic contribution of the project?

1. How has the economic contribution of the project materialised?

- [ ] Sales of manufactured product/equipment
- [ ] Royalties from licensing
- [ ] Cost savings
- [ ] Time savings
- [ ] Other, please specify : ____

2. How important is this economic contribution ?

- [ ] High economic contribution — Value: RM________________
- [ ] Medium economic contribution — Value: RM________________
- [ ] Low economic contribution — Value: RM________________

3. When has this economic contribution materialised?

- [ ] Already materialised
- [ ] Within months of project completion
- [ ] Within three years of project completion
- [ ] Expected in three years or more
- [ ] Unknown

C Infrastructural contribution of the project

1. What infrastructural contribution has the project had?

- [√] New equipment Value: RM _15,000_____________
- [ ] New/improved facility Investment : RM ___________________
- [√] New information networks
- [ ] Other, please specify: ____

2. How significant is this infrastructural contribution for the organisation?

- [√] Not significant/does not leverage other projects
- [ ] Moderately significant
- [ ] Very significant/significantly leverages other projects

D. Contribution of the project to the organisation's reputation

1. How has the project contributed to increasing the reputation of the organisation

- [ ] Recognition as a Centre of Excellence
- [ ] National award
- [ ] International award
- [ ] Demand for advisory services
- [ ] Invitations to give speeches on conferences
- [ ] Visits from other organisations
- [√] Other, please specify: ___New field not touched by any others______________

2. How important is the project's contribution to the organisation's reputation ?

- [√] Not significant
- [ ] Moderately significant
- [ ] Very significant

1V. National Impacts of the Project

A. Contribution of the project to organisational linkages

1. Which kinds of linkages did the project create?

- [ ] Domestic industry linkages
- [ ] International industry linkages
- [√] Linkages with domestic research institutions, universities
- [ ] Linkages with international research institutions, universities

2. What is the nature of the linkages?

- [ ] Staff exchanges
- [√] Inter-organisational project team
- [ ] Research contract with a commercial client
- [√] Informal consultation
- [ ] Other, please specify: ____

B. Social-economic contribution of the project

1. Who are the direct customer/beneficiaries of the project output?

Customers/beneficiaries:	Number:
Academia	8
Engineers (former students)	11

2. How has/will the socio-economic contribution of the project materialised ?

- [ ] Improvements in health
- [ ] Improvements in safety
- [ ] Improvements in the environment
- [ ] Improvements in energy consumption/supply
- [ ] Improvements in international relations
- [√] Other, please specify: _Awareness in alternatives to conventional hazardous refrigeration__⇒ increase in research ideas

3. How important is this socio-economic contribution?

- [ ] High social contribution
- [ ] Medium social contribution
- [x] Low social contribution

4. When has/will this social contribution materialised?

- [x] Already materialised
- [ ] Within three years of project completion
- [ ] Expected in three years or more
- [ ] Unknown

Date: **Signature:**

Lampiran 20

UTM/RMC/F/0024 (1998)

UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN
LAPORAN AKHIR PENYELIDIKAN

TAJUK PROJEK :

ENVIROMENTALLY FRIENDLY REFRIGERATION WITH THERMOACOUSTICS

Saya Dr Normah Mohd Ghazali
(HURUF BESAR)

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Nama & Cop Ketua Penyelidik

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