THERMAL PERFORMANCE OF A THERMOACOUSTIC STACK

NURUDIN BIN HABEED MOHD ABD SETTAR

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*To my beloved **mok** and **pok***

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From Abu Hurairah, Rasulullah Sallallahu alaihi wasallam said, “He, who does not thank people, does not thank Allah.” (Narrated by Abu Daud, Ahmad and Termidzi. Al-albani said it is shaheeh)

I wish to express my sincere appreciation and thanks to my supervisor, Assoc. Professor Dr. Normah Mohd Ghazali, for encouragement, guidance, critics and suggestions. Without her continued support and interest, this thesis would not have been the same as presented here.

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To my mother and father that always pray for my successful, all this things cannot pay for all what you all have done.

Above this all, my highness praises and thanks to Almighty Allah subhanahu waalla, the most gracious the most merciful, who gave me the knowledge, courage and patience to accomplish this research. May the peace and blessings of Allah be upon Prophet Muhammad Sallallahu alaihi wasallam.

ABSTRACT

The heat transfer process crucial to the thermoacoustic effects occurs in and near the stack region and current technology of the stack material and geometry has room for improvement. The latest recommended stack material is Mylar and it has been theoretically proven that pin-array stack performs better than other geometry. Stack gap recommended varies between researchers using different material and geometry. This study looked into the stack performance in terms of the temperature difference achieved between the stack ends for various locally available materials at different thickness and geometry. Experiments were conducted using PVC resonator tube with paper and film material as stack, at 0.1 and 0.2mm thickness. Parallel plate, spiral roll and the honeycomb geometry were tested. Results showed that the parallel plate stack made from the film gave higher temperature difference compared to that from paper operating with a stack gap of 0.45mm. A maximum of 3.5°C below the ambient temperature was achieved at the “cold” end for the system operating at 1atm and 22~24°C.

ABSTRAK

Proses pemindahan haba yang penting untuk kesan termoakustik berlaku berhampiran dan di kawasan ‘stack’ dan teknologi terkini pada bahan ‘stack’ dan geometrinya masih ada ruang untuk dilakukan pembaikan padanya. ‘Stack’ yang terkini yang dicadangkan ialah Mylar dan telah telah dibuktikan secara teori yang susunan pin memberikan keputusan yang lebih baik berbanding geometri yang lain. Celah ‘stack’ telah dicadangkan oleh beberapa penyelidik dengan bahan dan geometri yang berlainan. Kajian ini adalah untuk melihat prestasi ‘stack’ dari aspek perbezaan suhu yang akan dicapai di hujung ‘stack’ untuk pelbagai jenis bahan pada ketebalan dan geometri yang berbeza. Ujikaji di lakukan pada kertas dan filem pada ketebalan 0.1mm dan 0.2mm. Geometri jenis plat selari, lingkaran dan ‘honeycomb’ pula akan di uji. Keputusan menunjukkan plat selari filem menghasilan beza suhu yang lebih berbanding dengan plat selari kertas dengan celah gap 0.45mm. Suhu maksimum 3.5°C dibawah suhu sekitaran telah dicapai pada hujung sejukuntuk system yang beroperasi pada 1atm dan 22~24°C.

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LIST OF SYMBOLS

SYMBOLS

a	Sound velocity
δ_k	Thermal penetration depth
δ_{kn}	Normalized Thermal penetration depth
δ_ν	Viscous penetration depth
c_p	Heat capacity or Specific heat (in this thesis mostly for stack)
β	Thermal expansion coefficient
T_m	Mean Temperature
ΔT_m	Temperature difference
k	Wave number
ΔT_{mn}	Normalized Temperature difference
Γ	Normalized temperature gradient
$L_s / \Delta x$	Stack Length
L_{sn}	Normalized Stack Length
ε_s	Stack heat capacity correction factor
σ	Prandtl number
Π	Perimeter
p_o	Dynamic pressure amplitude
p_m	Average Pressure

y_o	Half Stack spacing
l	Half plate thickness
K_s	Thermal conductivity of stack
K	Thermal conductivity of working fluid
ρ_s	Density of stack
f_k	Rott function
$(\nabla T)_{crit}$	Critical mean-temperature gradient
x_s (x_m)	Mean stack position from the pressure
γ	Isobaric/isochoric
f	frequency
ω	Angular frequency
λ	Wavelength of acoustic standing wave
B	Blockage ratio/stack porosity
D	Drive ratio
Q_{cn}	Normalized Cooling Power
W_n	Normalized acoustic power
COP	Coefficient of performance
TA_{area}	Thermoacoustic area
VIS_{area}	Viscous area
TA (T_A)	Ambient temperature
TH (T_H)	Hot temperature
TC(T_C)	Cold temperature

CHAPTER 1

INTRODUCTION

1.1 Background

Nikolaus Rott (1980) defined thermoacoustic as studies generally dealing with effects in acoustic in which heat conduction and entropy of a medium play a role.

If a system converts acoustic into energy, it is called a thermoacoustic refrigerator while a system converting energy to acoustic is called a thermoacoustic prime mover. There are two modes of a thermoacoustic system: the small standing wave thermoacoustic and traveling wave thermoacoustic. This study will focus on the standing wave thermoacoustic.

In 1777, Byron Higgins discovered thermoacoustic. Even though this is not a refrigeration system, the thermoacoustic effects have initiated investigations. For example, Sondhauss in the year 1850 had started a thermoacoustic oscillation research which was the best research of this category. Table 1 shows some of the studies done so far.

Table 1.1: Thermoacoustic History

Year	By	Comments
The beginnings		
1777	Byron Higgins (B. Higgins, 1802)	Investigation of organ pipe type oscillations known as 'singing flames'. Hydrogen was used at the open end. (See Figure 1.1)
The interest		
1850	C. Sondhauss (C. Sondhauss,1850)	The best thermoacoustic oscillation research. Sondhauss tube is an open tube terminated in a bulb on the other and. (See Figure 1.2)
1859	Petrus Leonardus Rijke (P.L.Rijke, 1859)	Strong oscillation occurred when a wire screen is heated in a lower half of an open-ended pipe. This kind of tube was name 'Rijke Tube'. (See Figure 1.3)
1868	Gustav Robert Kirchhoff (G. Kirchhoff, 1868)	One of the earliest theoretical thermoacoustic studies. Involves the calculation of acoustic attenuation in a duct due to oscillatory heat transfer between solid isothermal duct wall and a gas sustaining sound wave.
1887	Lord Rayleigh (L. Rayleigh, 1945)	Qualitative explanation on Sondhauss oscillation.
1949	K.W. Taconis and J.J.M Beenakker (K.W. Taconis et al, 1949)	Taconis Oscillation which occurs in cryogenic storage vessels was discovered.
Theoretical study		
1962	R.L Carter, M. White and A.M. Steele (R.L.Carter et al,1962)	Improved Sondhauss tubes performance was found with placing suitable structures such as a stack.
1966	W.E.Gifford and R.C.	A pulse tube refrigerator with a low temperature

	Longsworth (W.E. Gifford et al, 1966)	difference was developed. The ratio between the cold and hot temperature is only 0.5 and this system operated at 1Hz with a pressure ratio of 4. (See Figure 1.4)
1975	P.Merkli and H.Thomann (P. Merkli et al, 1975)	Observed cooling effect around the velocity at antinodes in cylindrical resonator and present a good explanation and accurate theory for the effect.
1980	N. Rott (N. Rott,1980)	Study of the thermoacoustic theory. Rott's theory of thermoacoustic is considered the successful linear thermoacoustic theory.
1983	J.C. Wheatley, T. J. Hofler, G.W. Swift and A. Migliori (J.C. Wheatley et al, 1986)	Experiment on thermoacoustic heat engines. Develop a device known as 'thermoacoustic couple' or TAC with a good agreement with Rott's theory. This, however only produces small temperature difference.
Development		
1986	T.J. Hofler (T.J. Hofler, 1986)	The first Thermoacoustic Refrigeration created. This device has a cooling power of 6W using with 10.2 Bar Helium as the pressurized gas.
1992	S. L.Garrett, T.J.Hofler, J. Adeff and others (S. L.Garrett et al, 1989)	Develop a Space Thermoacoustic Refrigerator (STAR) This thermoacoustic refrigeration was flown on the Space Shuttle Discovery (STS-42) in January, 1992 with cooling power of 5W with mixed gas of 97.2% Helium and 2.7% Xenon in 10 atm pressurized.
2001	M.E.H. Tijani (M.E.H. Tijani,2001)	Develop thermoacoustic refrigeration with Cooling power of 4W using various mixed of gaseous such as: Helium / Helium-Argon / Helium-Kripton / Helium-Xenon with 10 bar of pressure.
2002		Cryogenics Division of Sumitomo Heavy Industries, Ltd was established. This company produced 'pulse tube cryocooler.' It is considered as the 1st commercial thermoacoustic refrigeration.

2004	Poese, M.E, S. Garrett and R. Smith	Develop commercial thermoacoustic chiller for Ben & Jerry's ice-cream. This collaboration was because of interest of environmental effect form the commercial refrigeration. The chiller has cooling power of 119 Watts With Helium in 10 atm pressure.

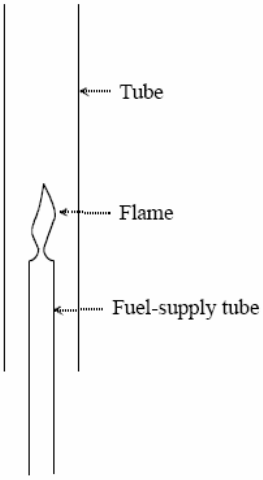


Figure 1.1: Singing Flame apparatus. (M.E.H. Tijani, 2001)

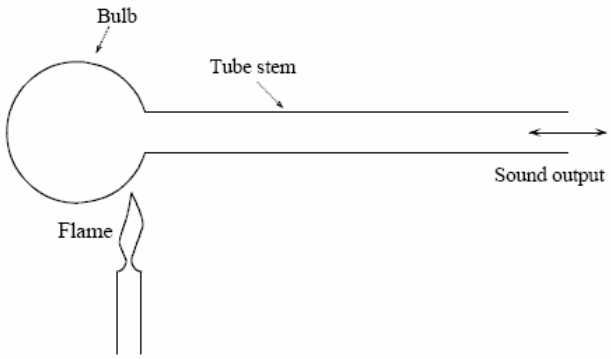


Figure 1.2: Sondhauss Tube (M.E.H. Tijani, 2001)

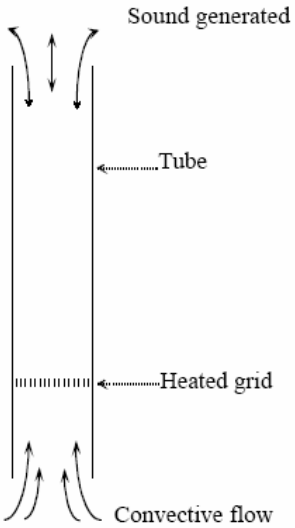


Figure 1.3: Rijke Tube (M.E.H. Tijani, 2001)

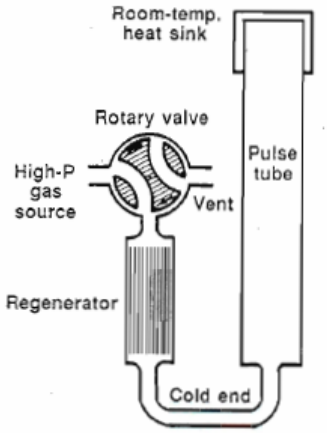


Figure 1.4: Pulse tube refrigerator (G.W. Swift, 1988)

The stack (also referred to as regenerators by some authors) is the place where the heat pumping process takes place. It should be located close to the pressure antinode of a standing wave. Figure 1.5 (a) shows a schematic of the stack and other important parts of the thermoacoustic refrigeration system. Because the location must be close to the pressure antinode, there are two ways of putting the stack in the resonator as shown in Figure 1.6.

It was Carter, et all (Carter, 1962) who were responsible of introducing the stack in the thermoacoustic system. Starting from here, the stack was used to increase the thermoacoustic effects. In 1980 Rott (N. Rott, 1980) studied the circular and parallel

stack. Later, his study on the stack was put into the Rott's Function diagram, a diagram which is important in determining the stack boundary layers. (G.W.Swift, 1988)

J.C. Wheatley, et al (J. C. Wheatley et al, 1986) then used tungsten as a stack with parallel plate geometry for his patented thermoacoustic device in 1986. In the same year, T.J. Hofler (T.J. Hofler, 1986) then used a camera film as a stack with spiral geometry for his PhD. His geometry was considered simple to fabricate. He also used fiber glass parallel plate stack for his Hofler Tube that was used to demonstrate to his students about the thermoacoustic effects. A year after that, J.C. Wheatley (J. C. Wheatley et al, 1986) used stainless steel parallel plate for his beer cooler.

G.W.Swift (G.W.Swift et al, 1990) then patented his Acoustic Crycooler in 1990. This Acoustic Crycooler used stainless steel parallel plates and Kapton sheet spiral wound as stack. W.P.Arnott, et al (W.P.Arnott et al, 1991) then studied square, rectangular and triangular pores for the stack. The studies of these stacks were added into the Rott's function diagram in the year 1991.

In 1992, STAR thermoacoustic refrigeration system was developed using Mylar™ with spiral roll as the stack. This was the big turning point in stack development, as many researchers after that used Mylar™ as stack because of its success. R.M. Keolian and G.W Swift (R. M. Keolian et al, 1995) and M.E. Hayden and G.W Swift (M.E. Hayden et al, 1997) mentioned the pin array stack. They proved that the pin-array is the best geometry for the stack. The main problem is the difficulties in fabricating the stack. With pin-array stack the problem of using low conductivity stack material does not arise.

M.E. Poese (M.E. Poese, 1998)) and M.E.H Tijani (M.E.H. Tijani, 2001) then used parallel plates with Mylar™ as the stack. O.G. Symsko in 2003 and 2004 used cotton wool and glass wool as the stack for his patented thermoacoustic refrigerator. It seems that stack material is still being studied for the development of a better thermoacoustic system.

1.2 Importance of the stack

The stack is considered as the heart of a thermoacoustic system. Development and continuous improvement of it can better the overall performance of a thermoacoustic system. The heat transfer process crucial to thermoacoustic effects occurs in and near the stack region and current technology of the stack material and geometry has room for improvement based on the background completed. Various researchers have recommended various stack gap using latest discovery of the best performance stack material (i.e. Mylar). Theoretical analysis has shown a pin-array as better than parallel plate but the spiral roll kind is easiest to be fabricated with an acceptable ease. This study will look into possibility of using locally available materials with ease of assembly to produce optimized thermoacoustic effects

1.3 Objectives

The objective of this project is to identify the optimized stack geometry (material) of a thermoacoustic system.

1.4 Scope

The scopes are:

- To analyze the factors that affects the thermal performance of current thermoacoustic stacks.
- To design and fabricate stacks for various materials (paper and film)
- To perform tests and analyses on the stack performance based on the temperature difference attained across the stack.

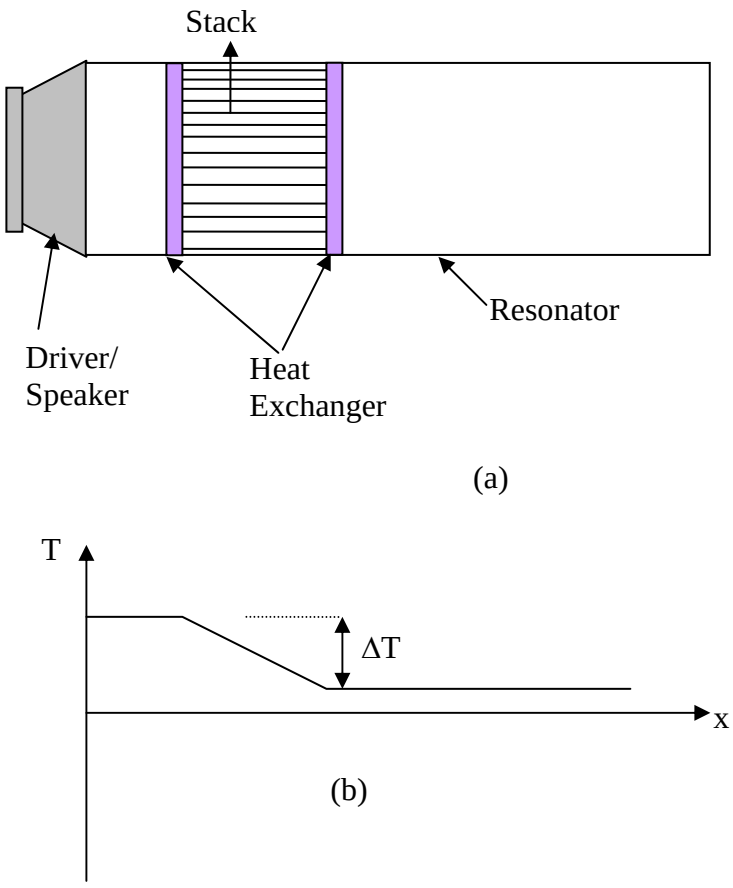
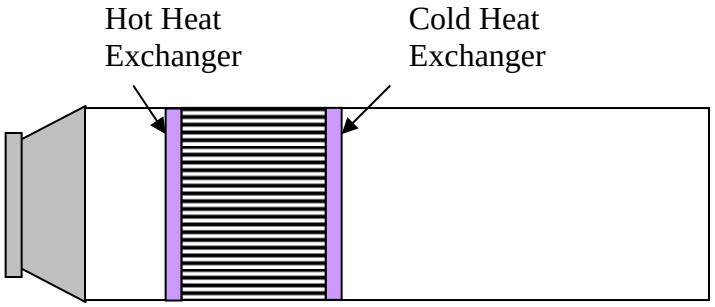
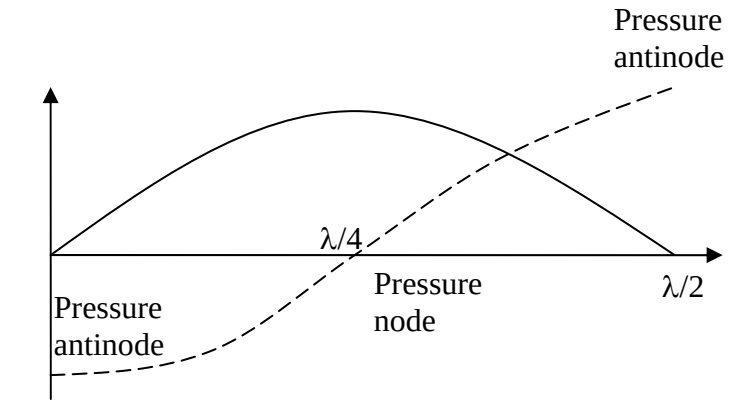


Figure 1.5: (a) A simple thermoacoustic refrigeration system (b) the temperature distribution along the resonance tube



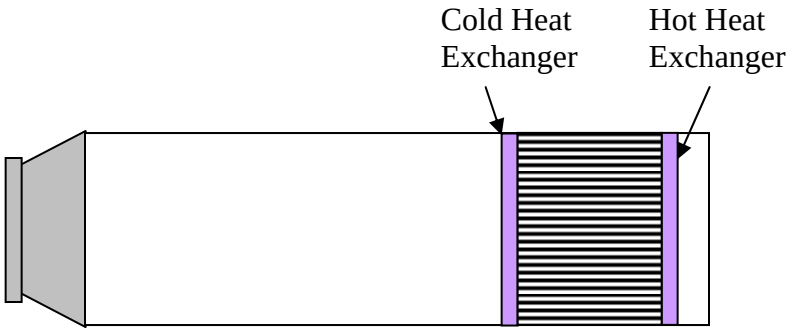
(a)



(b)

Pressure distribution

Velocity distribution



(c)

Figure 1.6: Stack position for λ/2 resonator

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