THE EFFECT OF FLOW FREQUENCY ON HEAT EXCHANGER USED IN THERMOACOUSTICS

CHIN JIA YU

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DECLARATION

I declare that this project report entitled "The Effect Of Flow Frequency On Heat Exchanger Used In Thermoacoustics" is the result of my own work except as cited in the references.

Signature : ....

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Thermal-Fluids).

Signature : ....

Supervisor‟s Name : ....

Date : ....

DEDICATION

To my beloved father and mother.

ABSTRACT

Heat exchangers play an important role in the performance of thermoacoustic devices. Due to the complexity of oscillatory flows, the interaction of sound wave energy and heat transfer in oscillatory flows is still not fully understood. The purpose of this study is to determine the effect of flow frequency on heat exchangers used in thermoacoustic system. A simple thermoacoustic model was developed using Computational Fluid Dynamics (CFD). Two flow frequencies were investigated; 13.1 Hz and 26.0 Hz. The model was validated by comparing the simulation results and theoretical results of *x*-velocity at the middle of the stack. The percentages of error were recorded based on axial velocity for one cycle where fluid flows forward and backward in a cyclic manner. During forward movement (positive value), the maximum error was 7.85%. As flow reversed, the maximum error became 8.85%. Laminar model and SST k-omega model were used for simulation of 0.30% and 0.83% drive ratios, respectively. The total surface heat flux at hot heat exchanger increased with increasing value of frequency. However, as the drive ratios increased the heat transfer performance for 26.0 Hz flow frequency dropped. This may be related to the effect of turbulence and vortex structures. The vortex structures were found distorted as flow frequency increases. Further research is required to study the effect of turbulence and behaviour of vortex structures.

ABSTRAK

Penukar haba memainkan peranan yang penting dalam prestasi sistem termoakustik. Oleh kerana pengaliran ayunan yang rumit dalam sistem tersebut, interaksi antara tenaga gelombang bunyi dan pemindahan haba dalam aliran ini masih tidak dapat difahami dengan sepenuhnya. Tujuan kajian ini adalah untuk mengenalpastikan kesan kekerapan aliran yang digunakan pada penukar haba dalam sistem termoakustik. Sebuah model termoakustik yang ringkas telah diwujudkan dengan menggunakan perisian Pengkomputeran Dinamik Bendalir (CFD). Model ini telah disahkan dengan membandingkan kehasilan daripada simulasi CFD dan kehasilan teori berdasarkan x-halaju yang diletakkan di pertengahan timbunan model. Peratusan ralat direkodkan berdasarkan x-halaju untuk satu kitaran di mana cecair sistem mengalir dengan cara berkitaran. Semasa cecair mangalir ke arah hadapan, kesilapan ralat maksimum adalah 7.85% manakala kesilapan maksimumnya berubah menjadi 8.85% apabila pengaliran diterbalikkan. Model laminar digunakan untuk aliran dengan nisbah memandu berukuran 0.30% manakala model SST k-omega digunakan untuk nisbah memandu pada kadar 0.83%. Hasil kajian menujukkan jumlah permukaan fluks haba di penukar haba panas akan meningkat dengan peningkatan nilai kekerapan yang digunakan. Walau bagaimanapun, prestasi pemindahan haba untuk kekerapan aliran 26.0 Hz berkurangan apabila nisbah memandu dinaikkan. Ini kemungkinan berlaku disebabkan oleh kesan pergolakan dan struktur vorteks. Struktur vorteks ditemui berputar apabila kekerapan aliran ditambahkan. Kajian lanjut diperlukan untuk mengkaji kesan pergolakan dan kelakuan struktur vorteks ini.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBEREVATIONS

CFD	-	Computational Fluid Dynamics
DR	-	Drive Ratio
HHX	-	Hot Heat Exchanger
PISO	-	Pressure-Implicit with Splitting Operators
TA	-	Thermoacoustics
TAE	-	Thermoacoustic Engine
TAR	-	Thermoacoustic Refrigerator
TASE	-	Thermoacoustic Stirling Engine
UTeM	-	Universiti Teknikal Malaysia Melaka

LIST OF SYMBOLS

π	=	Pi
f	=	Frequency
Hz	=	Hertz
P_a	=	Pressure at pressure antinode
k_a	=	Wave number
c	=	Speed of sound
x_1	=	Location of one end of the stack
x_2	=	Location of another one end of the stack
t	=	Time taken
θ	=	Phase
P_1	=	Inlet pressure
P_m	=	Mean Pressure
m_1	=	Outlet mass flux
λ	=	Wavelength
δ_K	=	Thermal penetration depth
k	=	Thermal conductivity
ω	=	Angular frequency
ρm	=	Mean of gas density
cp	=	Constant pressure heat capacity per unit mass
δ_v	=	Viscous penetration depth
μ	=	Dynamic viscosity
μ_0	=	Reference viscosity
T_0	=	Reference temperature
b_μ	=	Temperature exponent

CHAPTER 1

INTRODUCTION

1.1 Background

Thermoacoustics is a system which involves the interaction between heat and sound wave energies. The stack with both cold and hot heat exchangers on each side is the main component of a thermoacoustic system where the interaction of heat and sound waves take places. When a fluid is flowing through an object or solid boundaries, the fluid particles will bump onto the wall of the solid boundaries and then heat energy will release. The space between the plates in the stack is important. It is just similar to a set of sandwich; the fluid particles are like the contents of sandwich and the solid boundaries are the sandwich bread. If the gaps are too small, the effects of viscous will cause the working fluid to lose much of energy to overcome the friction and the device will become inefficient. If the gaps are too large, there will be not enough contact between the gases and the solid boundaries to produce suitable temperature oscillations (Swift, 1988).

The latest designs of thermoacoustic devices have the advantage of not having or consist of less moving parts. The term of thermoacoustics was first developed by Rott (1980) who came out with the theoretical approach of thermoacoustics field. The interactions between sound and heat energy are invisible and difficult to be revealed within everyday sound propagation and transmission processes. However, this interaction can be improved if the properties of the acoustic oscillation are improved such as oscillation with high intensity, high mean pressure or high drive ratio. Thermoacoustic devices are usually categorized into engine systems and refrigerators. Examples of the thermoacoustic engines and thermoacoustic refrigerators are shown in Figure 1.1 and 1.2 respectively. The thermoacoustic engine will convert thermal energy caused by a temperature gradient produced from the both ends of an object, into acoustic energy whereas the thermoacoustic refrigerator utilizes a sound wave enforced along the object in order to generate the temperature gradient (Swift, 1988).

Figure 1.1 Qnergy‟s Thermoacoustic Stirling Engine (TASE)

(Retrieved from http://www.qnergy.com/thermoacoustic-stirling-engine-)

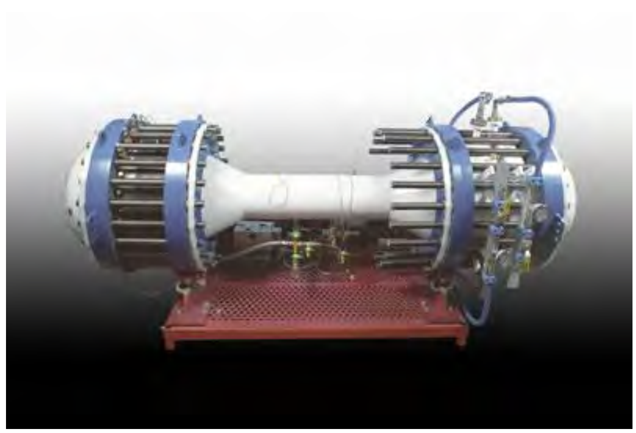

Figure 1.2 TRITON Shipboard Thermoacoustic Cooler

(Retrieved from http://www.acs.psu.edu/thermoacoustics/refrigeration/triton.htm)

A simple explanation about thermoacoustic engine may be explained with the aid of Figure 1.3 and the corresponding thermoacoustic process is shown in Figure 1.4 which is similar to a basic engine cycle as taught in most thermodynamics textbooks. In thermoacoustics, power may be produced by an engine when there is an input of high temperature gradient. This happens near the stack as shown in Figure 1.3. The hot and cold heat exchangers at both ends of the stack creates huge temperature drop. As a result, an acoustic oscillation occurs. This oscillation may be translated into electrical current if suitable conditions are met. The hot side of the stack is able to transfer energy into the gas particle in the form of heat as the gas particles keep colliding onto the wall of stack. The air as well as the heat energy, then oscillates to the low pressure point on the cold side of the stack. As the gas pressurizes, the gas temperature also increases. When the gas temperature on the cold side of stack is higher than that of the heat sink, it will transfer energy into the heat sink in form of heat. The air then depressurizes as it will moves back to the hot side where the cycle starts over again. Notice that this kind of air flow back and forth is called as oscillatory flow.

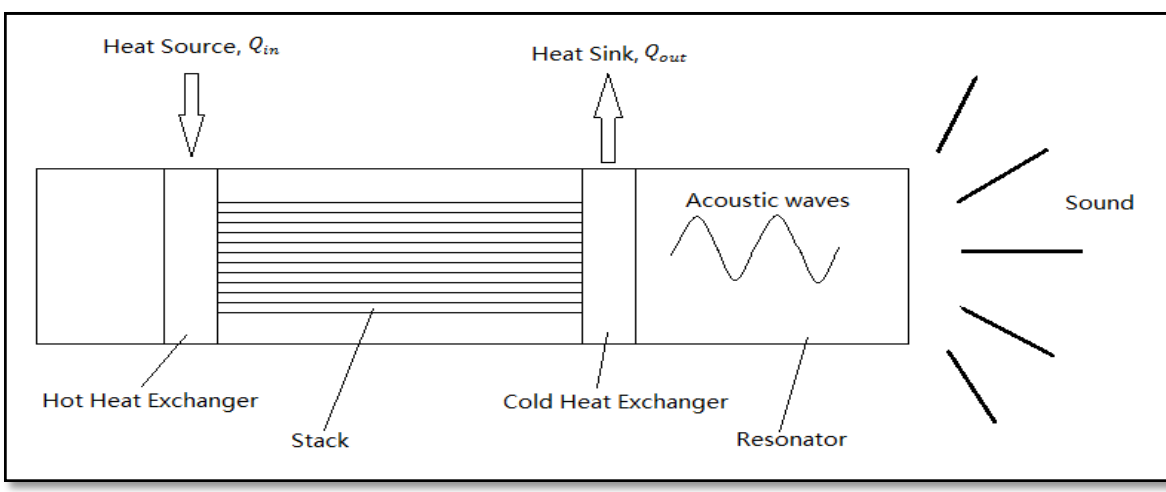

Figure 1.3 Illustrations on position of heat exchangers and stack in a standing-wave thermoacoustic engine

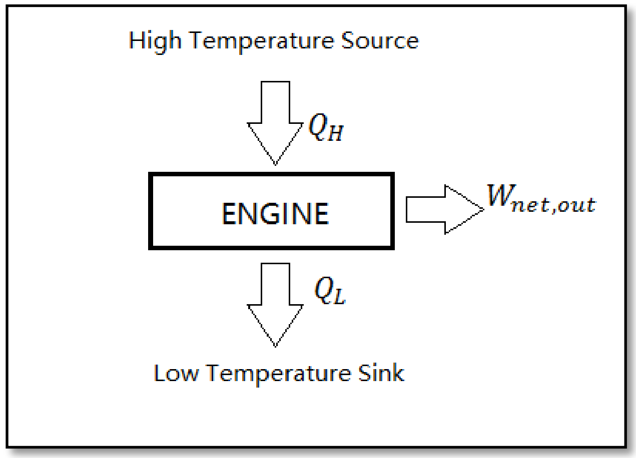

Figure 1.4 Process cycle of thermoacoustic engine

1.2 Problem statement

It is important to understand the behavior of the flow and heat transfer phenomena inside the thermoacoustics system and develop more of this green and sustainable technology in our industry. Current solution used in designing the thermoacoustic system depends on a one-dimensional linear model. However, in practical system, the flow may consist of abnormalities such as flow characteristics, natural convection, streaming and vorticity. These effects are investigated so that a proper understanding may be gained. The study on flow frequency on heat exchanger in such system is also important. There are different ranges of frequencies that can be used for different thermoacoustics applications. As the flow frequency of the working fluid is changed, the physical and flow properties of the working fluid near the plates will also change. This may somehow affect the interaction between the heat and sound wave energies inside the system. The changing of geometry may also create disturbances on the flow. Therefore, the study on flow frequency on heat exchangers used in thermoacoustics system will be an interesting topic.

1.3 Objectives

The objectives of this study embark:

i. To develop thermoacoustic model using ANSYS software.

ii. To validate the model with available published work (i.e. experimental and/or theoretical data).

iii. To analyse and study the effect of flow frequency on the heat exchanger used in therrmoacoustics system.

1.4 Scope of project

There are several parameters that can be discussed and varied in order to study the condition of heat exchanger which is the main component for the process of energy conversion between heat transfer and fluid flow. In this study, operating frequency of the working fluid which passes through the heat exchangers will be the only parameter studied. A simple model will be formulated by using ANSYS Fluent – Computational Fluid Dynamics (CFD) software for the effect of flow frequency on the heat exchanger will be carried out.

CHAPTER 2

LITERATURE REVIEW

2.1 Thermoacoustics

Thermoacoustics (TA) comes from the words of "thermo" and "acoustics" which is the combination of heat transfer and propagation of sound waves energy. The conversion of the process which involved both acoustic and thermal energies can be produced by using the effect of thermoacoustics. Rayleigh (1877) was the first to give a qualitative explanation or description about thermoacoustic effects. In his research of "The Theory of Sound", published in 1887, he discussed about the way to produce temperature differences using acoustic wave oscillations. His work then remained untouched for around eighty years until Rott began a series of research and publications. Rott (1969) became the pioneer in deriving the precise equations for pressure contribution, motion of particles and time-averaged in energy transport which occurred in a channel with a sinusoidal oscillation and a temperature gradient (Swift, 2001).

When the temperature of gas-filled tube decreased from room temperature to cryogenic temperature with spontaneous oscillations, the problem of Taconis oscillations started gaining attention from researches. Rott selected this problem as his first research topic to answer the curiosity about why the tube vibrates and sings loudly after being removed from a coolant. Taconis oscillation is one of the types of thermoacoustic oscillations that happen when a gas-filled thin tube is inserted into cryogenic liquid of helium. Cryogenic is a study of production and behaviour of materials at very low temperatures. It can be said that when a tube is closed at the warm side and the length of tube is extended from room temperature to a region of liquid helium temperature (very low temperature region), the large temperature gradient will produce Taconis oscillations (Meyer Tool & Mfg. Inc., 2011). In old centuries, Rott"s approach of thermoacoustic can be considered as successful linear thermoacoustic theory as he formulated the fundamental mathematical concepts in order to describe the sound oscillations of gas particles inside a channel with an axial temperature gradient and the lateral channel dimensions of the gas thermal penetration depth, δ_k. Gas thermal penetration depth is the distance that heat can diffuse through the gas in a time of $1/\pi f$, where f is the frequency of the sound wave (Jinshah et. al., 2013).

2.2 Thermoacoustic devices

Thermoacoustic devices can functions in two ways; one is to produce work using heat which is called as prime mover (heat engine); another way is to produce heat by using work and this device is normally known as heat pump (refrigerator). The schematic diagrams of thermoacoustic prime mover and heat pump are shown in Figure 2.1 (a) and Figure 2.1 (b) respectively. Stirling engine is one type of heat engine that consists a lot of moving parts which operated by cyclic expansion and compression of working air at different temperatures. In 1969, William Beale realized that the forces acting on the connecting rods of the Stirling engine should be made small resulting in free-piston devices. After realizing that the time phase between velocity and pressure inside the Stirling engine is same as in acoustic travelling wave, Peter Ceperly suggested on removing every moving parts and keeping only the working gas itself inside the Stirling engine. Not long after that, the Los Alamos group started their research involving the development of standing-wave thermoacoustic engines and refrigerators with different time phasing from Ceperly"s idea and Stirling engine principle (Swift, 2001).

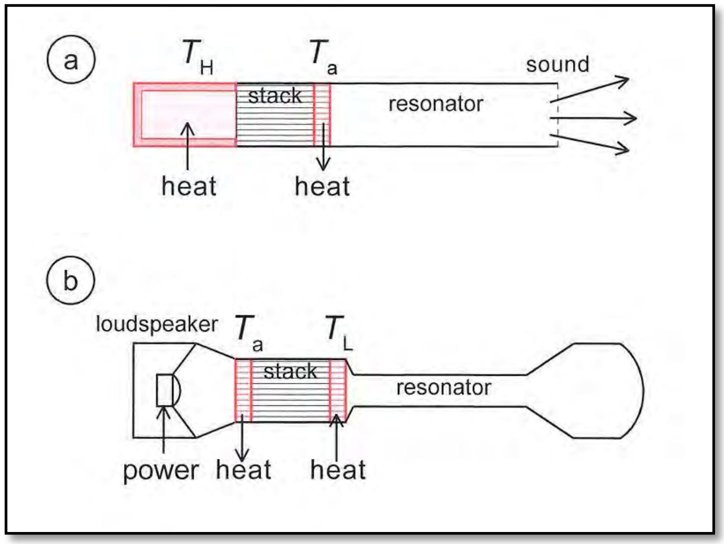

Figure 2.1 (a) Schematic diagram of a thermoacoustic prime mover;

Figure 2.1 (b) Schematic diagram of a thermoacoustic heat pump

(Retrieved from https://en.wikipedia.org/wiki/Thermoacoustics)

When there is a temperature gradient produced in the regenerative unit, pressure variations and velocity will be amplified until a steady state is achieved, a loud noise will be produced (Trapp *et al.,* 2011). According to Swift (2001), there will be a parcel of working gas or fluid flowing across the parallel plates which are having temperature difference. The parcel of gas will absorb heat from hot heat exchanger on one side of the stack and then it oscillates to another side of the stacks and gives out the heat. Hence there will be a pressure difference on the parcel of gas. When the parcel is having high pressure, thermal expansion occurs and when the pressure is low thermal contraction takes place. The cycle will repeat and hence work will be produced. The sum of all the parcels in the stack is the total work produced by the engine (Swift, 2001).

Nowadays, thermoacoustic devices have gained more attention due to its independence on mechanical moving parts and hence, they became more efficient. Furthermore they can be powered easily with natural sources such as solar energy or waste heat energy and the working medium is kind of environmental-friendly. The fabrication costs of such devices are low and they are reliable (Piccolo, 2011).

2.2.1 Thermoacoustic engines

Yazaki *et al.* (1998) established the first travelling wave thermoacoustic engine (TAE) in the kind of looped-tube that was functioning well. Basically, the working medium that is used in the TAE is either pressurized air or noble gases (e.g. helium or argon). However, different types of liquid can also be used as working medium in the standing wave TAE systems such as liquid sodium, sea water or combination of gas and liquid system (Tang *et al.*, 2011). These kinds of working fluids are used to reduce the losses in the system which normally having a low Prandtl number. Prandtl number is defined as the ratio of momentum diffusivity to thermal diffusivity (Saechan, 2014).

For the standing wave TAE, the gas particles will start to oscillate when the temperature gradient produced along the stack of parallel plates reaches a maximum value which is called as onset temperature gradient. The oscillations promote the energy conversion from heat to acoustic energy (Atchley, 1992). The acoustic power produced will overcomes the thermal losses inside the system. Then the amplitude of acoustic power in the resonator increases speedily and this will facilitates the heat transfer. The oscillation will be constant if the power of heating is sufficient enough and finally it will reach a steady state. Otherwise, the on-off process may be occurred if the heating power is only enough for its self-oscillations. When the temperature of the hot end stack falls under a specify value, the oscillations will stop