SIMULATION AND EXPERIMENTAL DESIGN OF THERMOACOUSTIC HEAT ENGINE

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DEDICATION

In the name of Allah, Most Gracious, Most Merciful

Among the signs of a person who always relies on his deeds is the lack of ar-raja ' (the hope of Allah's mercy) on the side of the mortal nature. - **Ibn Athaillah**

“*Di antara tanda seseorang yang selalu bergantung pada perbuatannya adalah kurangnya ar-raja ' (harapan dengan rahmat Allah) di sisi sifat fana. -* ***Ibnu Athaillah***”

This work is dedicated to my mother, **Rokiah @ Natrah binti Mustaffa**, and to my late father, **Allahyarham Abd Rahim bin Mohd Noh** with great prayers for me.
Special thanks to mother, father and my sibling
Rosiffa Murni, Rossiana and Mohd Izzat Nazmi

Thank you to my wives **Haryanti binti Mat Desa** and **Azlida binti Abdullah** for their unbelievable support and understanding throughout this work

To my children,
Mohammad Izzuddin Al Qasimi
Raudhah An Najah
Ahmad Izzat
Mohammad Nur Al Fateh
Alya Izzah
Aalima Itqan
Arfa Imani

Last but not least, to my beloved Gurus; As Sheikh, Al Faqir IlaLlah, **Al Walid Tok Ku Mohamad Ibrahim** and Almarhum As Sheikh, Al Faqir IlaLlah, **Wa Mat** in which the bless of Allah had let their kind words kept on inspiring me the most through out my times with this pure intention is ***from Allah s.w.t. with Allah s.w.t. and to Allah s.w.t.***

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ABSTRACT

Renewable energy is an important field in providing reliable and sustainable energy to the world. Wasted heat is found to be a good source of renewable energy. This wasted energy can be found almost in all types of production processes, including ~~the~~ heat exchanger. The heat energy dissipated from these processes is unutilized leading to inefficiency in the system. The need to harvest the wasted heat is essential in making sure the energy can be further utilized for other applications. Previous research works conducted on harvesting heat into sound in the system is still lacking and there is no specific standard can be employed. This research focused on analysing and developing a reference method of harvesting sound from a thermoacoustic heat engine system. A simulation approach was employed to investigate the performance of heat flow on the heat exchanger and related components. A standard test rig was designed to evaluate the performance of heat transfer experimentally. A comprehensive laboratory work was set-up to collect ample data to obtain the correlation of acoustic sound pressure-volume due to heat transfer performance by the oscillatory flow on the thermoacoustic system. The design of the developed thermoacoustic engine was able to produce waste heat in the range between 200°C and 700°C, and the harvested sound frequency ranged from 20 Hz to 2 kHz. From the experimental study, the sound level started at 4 s to 8 s and reaches a steady-state at 10 s. The temperature gradient on stack performance was 8.45°C/mm with a temperature difference at the steady-state point of 300°C. The spectrum analysis amplitude reached 133.5 dB with the frequency value of 397.5 Hz. The pressure-volume analysis has proved the existence of both isochoric and isothermal process through the gas bucket brigade phenomenon as the lead compression and expansion happened at the stack wall between the sound pressures of 12.94 Pa and 20.15 Pa. The finding confirmed that the sound energy from the heat oscillation can be harvested and a standard method has been developed. This study also confirmed the presence of a thermoacoustic cycle on the stack wall. This finding is significant as it provides a new standard in harvesting sound from the thermoacoustic heat engine. The efficiency of the system was successfully improved by 40% and the wasted energy was successfully harvested for further applications.

ABSTRAK

Tenaga boleh diperbaharui merupakan bidang yang penting dalam menyediakan tenaga yang boleh dipercayai dan lestari kepada dunia. Haba terbuang didapati menjadi sumber tenaga boleh diperbaharui yang baik. Tenaga yang terbuang ini boleh didapati hampir pada semua jenis proses pengeluaran, termasuk penukar haba. Tenaga haba yang terhasil dari proses ini yang tidak dapat digunakan menyebabkan ketidakcekapan dalam sistem. Keperluan memenafaatkan haba yang terbuang sangat penting bagi memastikan tenaga tersebut dapat digunakan seterusnya untuk aplikasi lain. Kerja-kerja penyelidikan sebelumnya yang dilakukan untuk memenafaatkan haba bagi menghasilkan bunyi di dalam sistem masih kurang dan tidak ada standard khusus yang dapat digunakan. Penyelidikan ini memfokuskan kepada menganalisis dan membangunkan kaedah rujukan untuk memenafaatkan bunyi dari system enjin haba termoakustik. Pendekatan simulasi telah digunakan untuk mengkaji prestasi aliran haba pada penukar haba dan komponen yang berkaitan. Rig ujian standard telah direka bentuk untuk menilai prestasi pemindahan haba secara eksperimen. Kerja makmal yang menyeluruh telah disediakan untuk mengumpulkan data yang mencukupi bagi memperolehi kaitan tekanan akustik bunyi-kekuatan bunyi disebabkan prestasi pemindahan haba oleh aliran ayunan dalam sistem termoakustik. Reka bentuk enjin termoakustik yang dibangunkan mampu menghasilkan haba terbuang dalam julat antara 200°C dan 700°C, dan frekuensi bunyi yang dimenafaatkan dalam julat dari 20 Hz hingga 2 kHz. Dari kajian eksperimen, tahap bunyi bermula pada 4 s hingga 8 s dan mencapai keadaan stabil pada 10 s. Kecerunan suhu pada prestasi susunan ialah 8.45°C/mm dengan perbezaan suhu pada keadaan stabil 300°C. Amplitud analisis spektrum mencapai 133.5 dB dengan nilai frekuensi 397.5 Hz. Analisis tekanan-isipadu telah membuktikan kewujudan kedua-dua proses setekanan dan sesuhu melalui fenomena pasukan timba gas bilamana pendahulu pemampatan dan pengembangan di dinding susunan berlaku antara tekanan bunyi 12.94 Pa dan 20.15 Pa. Penemuan ini mengesahkan bahawa tenaga bunyi dari ayunan haba dapat menafaatkan dan kaedah standard telah dapat dibangunkan. Kajian ini juga mengesahkan terdapat kitaran termoakustik di dinding susunan. Penemuan ini adalah signifikan kerana ia menyediakan standard baru dalam memenafaatkan bunyi dari enjin haba termoakustik. Kecekapan sistem ini telah berjaya ditambahbaik sebanyak 40% dan tenaga yang terbuang berjaya menafaatkan untuk aplikasi selanjutnya.

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LIST OF ABBREVIATIONS

Delta EC	-	Design Environment for Low Amplitude

ThermoAcoustic Energy Conversion

CFCs	-	Chlorofluorocarbons
CFD	-	Computational Fluids Dynamics
TWTAPM	-	Travelling Wave Thermoacoustic Prime Mover
TAHE	-	Thermoacoustic Heat Engine
FSI	-	Fluid Structure Interaction
COP	-	coefficient of performance
TAPM	-	thermoacoustic prime mover
TRA	-	thermoacoustic refrigerator
PT	-	plate thickness
PS	-	plate spacing
HHX	-	Hot Heat Exchanger
AHX	-	Ambient Heat Exchanger
He	-	Helium
Ar	-	Argon
CO2	-	Carbon dioxide
N2	-	Nitrogen
TAPMs	-	Thermoacoustic Prime Movers
TX	-	tube-array
HX	-	heat exchanger
PX	-	power-law heat exchangers
RPN	-	Reverse Polish Notation
CHX	-	Cold Heat Exchanger
HHX	-	Hot Heat Exchanger
Srough	-	Surface Roughness

LIST OF SYMBOLS

$\dot{W}h,regen$	-	Acoustic power
Lsn	-	Normalized position of stack
Δx	-	Change of distance
δk	-	Thermal penetration depth
ΔT	-	Temperature difference
Q	-	Heat flux
η	-	Global efficiency
Pel	-	Electric power
TH	-	Hot temperature
TA	-	Ambient temperature
L	-	Resonator length
f	-	Frequency
PA	-	Acoustic pressure amplitude
W	-	Acoustic power generated
Xs	-	Length of stack
σ	-	Prandtl number
fk	-	Transition from isothermal to adiabatic
fv	-	Transition from viscous flow to the viscosity
hv	-	Thermoviscous
TBeg	-	Beginning temperature
$\|p\|$	-	Magnitude acoustic pressure
Ph(p)	-	Phase acoustic pressure
$\|U\|$	-	Magnitude volume velocity
Ph(U)	-	Phase volume velocity
e	-	Surface Roughness
P	-	Pressure of gas
V	-	Volume of gas
R	-	Gas constant and
T	-	Temperature
Qin	-	Rate of heat supply

A	-	Cross Sectional Area of the Resonator
Cacs	-	Acoustical Compliance
a	-	Sound Speed [m/s], p. 45
Cp	-	Isobaric Heat Capacity
d	-	Distance from closed end of resonator that separates compliance and inertance for a lumped element system
f	-	Frequency
F	-	Shape Factor , p. 42
GasA/A	-	Porous area of stack material
H	-	Rate at which Total Energy flows
K	-	Wavenumber
L	-	Length of the Resonator
Lacs	-	Acoustical Inertance
Lt	-	Length of Toroidal Streaming Cell
M	-	Mean Molecular Weight of Gas
P_1	-	Acoustic Pressure
Pm	-	Mean Pressure
Pr	-	Prandtl Number
Qcond	-	Heat due to Thermal Conduction
Qrad	-	Heat due to Thermal Radiation
R	-	Radius of Resonator
r	-	Radial Distance from Axis of Resonator
rh	-	Hydraulic Radius
R	-	Universal Gas Constant
T1	-	Oscillating Temperature
Tm	-	Mean Temperature
t	-	Time
U_1	-	Volume Velocity
Vc	-	Volume of a compliance segment

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Sound waves in gas are often referred to as displacement and pressure shocks. In fact, temperature fluctuations are also present with pressure fluctuations. One of the reasons for the growing interest in thermoacoustic stems from its potential to protect the environment as it is a technology of renewable energy (Abdoulla et al., 2017). Thermoacoustic prime mover is to design an efficiently changing waste heat energy to electricity energy. Figure 1.1 shows a process of thermoacoustic interaction phenomena.

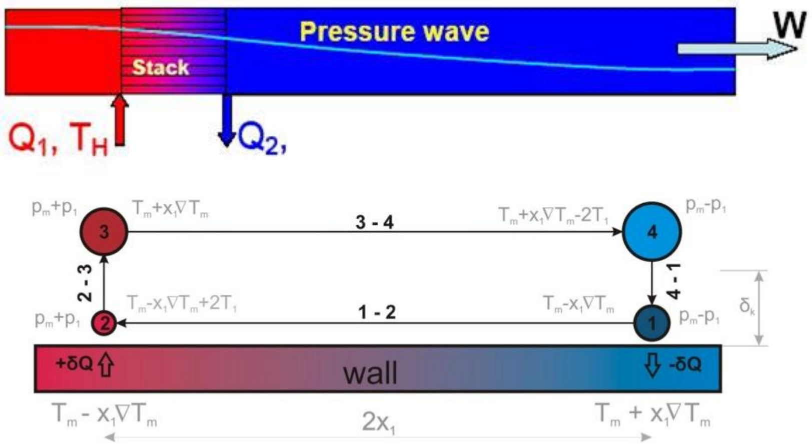

Figure 1.1 Thermoacoustic interaction phenomenon

This phenomenon has a four-step cycle, the properly phased heating with compression and expansion of the gas. When work has been done on the gas, the vibration is encouraged. In steady state operation, the work input per cycle is equal to the sum of the work absorbed by dissipative mechanisms where it has a process of viscous and thermal losses in the stack and resonator walls (Swift, 1988). Then acoustic energy is produced. With sustained oscillations within the resonator, each gas parcel must be at a position where the stack is at a different temperature from the adiabatic temperature change of the gas. That fact leads to a concept of a critical temperature gradient for the acoustic oscillations to be maintained.

World today, is facing the threat of a dual energy. First, on the supply side of energy equation, there is a lack of adequate and safe energy reserves at an affordable price, where countries bound to be affected. Second, on the perspective of demand, overconsumption of energy has become the prominent factor that caused reducing natural resources and environmental destruction, from oil spills to groundwater pollution. What is more threatening is that this demand is rising continuously. Figure 1.2 shows the basic of renewable energy method from nature source. World Energy Survey in years 2012 by the International Energy Agency, IEA (REN 21, Renewables Now, n.d.) estimates this energy global, demand are increased by more than one-third of 2035. China, India and the Middle East of country is contributing to this 60% increase of energy demand.. The revolution a drive, fuel shortages, such as diesel, natural gas and mazut, led to halts in power stations and power outages in some governors.

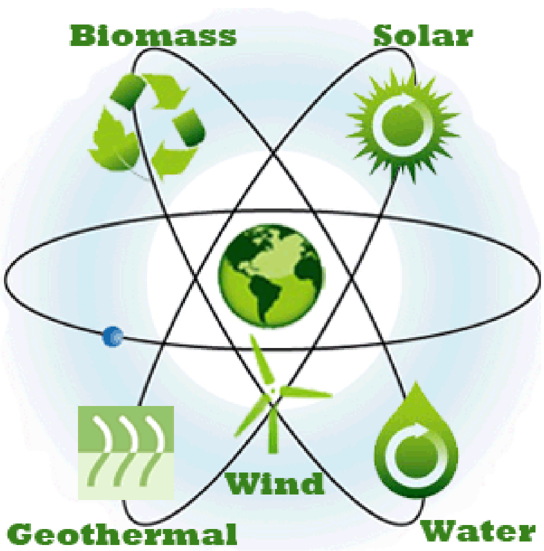

Figure 1.2	Basic of renewable energy method from nature source

There are two solutions that could be used to fill this energy gap. First, to reduce the demand for energy efficient. consumption.Second energy supply have to increased. This issue has to address.This study has recently, the thermal energy to convert acoustic values thermoacoustic heat engine to generate electricity or sound, producing energy. Half of the increment in global energy use are for generation of electricity to meet growing domestic needs for lighting, communications, cooling and water supply. The decrease in fossil fuel production, which necessitates the control of demand for fossil fuels, will increase energy demand, and to increase the geographic diversity and fuel supply mitigating climate-destabilising emissions become more critical than ever. Figure 1.3 shows the mutual technology on energy harvesting technique. The thermoacoustic phenomenon was first discovered by a glass blower in the 19th century, and has found the sound produced by heating a glass tube at one end. Started 1985, the designed and produced the first thermoacoustic device by John Wheatley and Swift is produced (Swift, 1988).

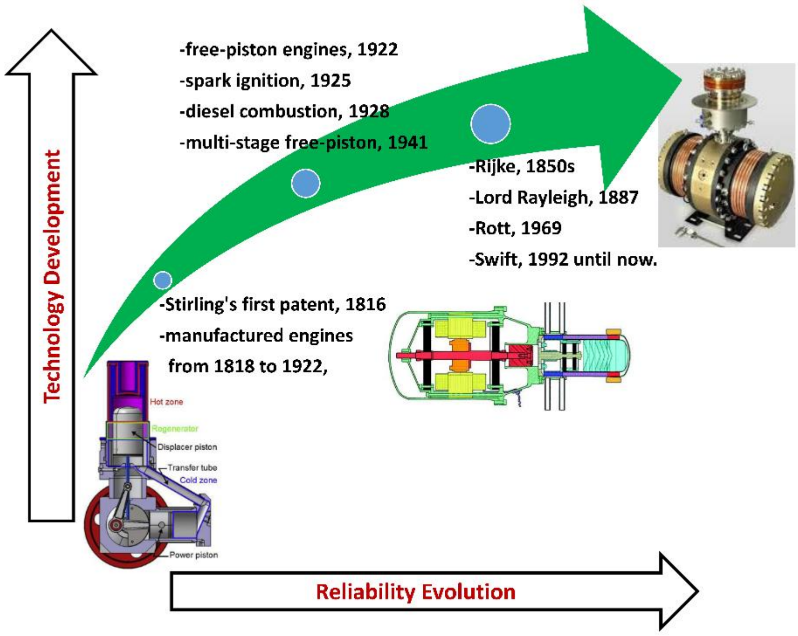

Figure 1.3   Mutual technology on energy harvesting technique

Currently two types of thermoacoustic devices, first the heat engine or the main carrier in which temperature is converted to acoustic power; and second hot or cold pumps to which the pump can emitheats. They have some non moving parts, require little maintenance and production of thermoacoustic engines are very reliable and cheap. These features make it effective for remote power generation or mobile applications. This requirement as a kind of wind energy and solar energy can be met by renewable energy, reduce the use of fossil fuels and provide a consistent and reliable source of electricity.

Typically, for example, especially on farms the generators are used to provide electricity during power outages, and out of the absence of built-in power supplies, for example, camping trips and on construction sites. Conventional generators require expensive, non-renewable and hazardous gas-producing gasoline or fossil fuels that contribute to air pollution and climate change.

An environmentally friendly condition, the thermoacoustic heat engine has operated are using air or noble of gases for a friendly environment.Thermoacoustic heat engine, an independent power converter or solar power plant to generate several power converters can be integrated to the solar energy concentrator. Especially in remote areas that are not connected to the home network, this will be very useful in the production of small houses and industries.

One of the key challenges in today's modern world, it aims to produce energy at a cost competitive to get the thermoacoustic heat engine. Engine locally quantities sold on the market in abundance, it uses relatively cheap and there is no special requirement, ie steel tubes for solar energy glass and convergence thermoacoustic heat engines. Over the last few decades, the key constraints in developing renewable energy have been ineffective. The average cost of electricity is much cheaper than other similar technology generated by the thermoacoustic engine.

In addition, the engine uses the highest degree of efficiency available. For all heat engines, it has a limitation to the heat engine produced an efficiency, even the best engine cannot convert 100 percent of the inlet temperature according to laws of thermodynamics. The addition of this limit is the temperature at which the heat enters the engine and the ambient temperature at which the exhaust engine consumes its heat.This obstacle value is called the Carnot cycle efficiency.

Emphasising the need to switch from extensive fossil fuel use to renewable energy sources., The formation of fossil fuel takes millions of years and, instead of mentioning the harmful emission of toxic gases into the atmosphere as a result of the combustion of fossil fuel, causes the depletion of reserves much faster than the new ones. Moving towards renewable energy resources is essential to meet the growing energy needs and to counter global environmental challenges.

1.2 Research Motivation

These days, renewable energy is important as the technology reaches high demand in saving the earth to provide energy. As the limitless on energy sources, renewable energy technique become are wonderful options. Moreover, the energy will not run out of them, unlike fossil fuels that we currently depend upon which will eventually be drained. Another great advantage of using renewable energy is that many of them do not cause water and air pollution in the way of burning fossil fuels. In 2006, approximately 18% of global energy consumption, renewable energy, 13% coming from traditional biomass, mostly used for heating and 3% is derived from hydropower (Demirbas, 2006). New renewable energy, such as small hydro, modern biomass, wind, solar, geothermal and biofuels, accounts for 2.4% and is growing rapidly. Renewable energy in electricity generation portion is 18%, 15% hydro and 3.4% of global electricity coming from renewable energy sources (Owusu & Asumadu, 2016) Thermoacoustic is one of renewable energy that included thermodynamic principles and acoustic principles. A sound wave produced by a gas is an expression of pressure displacement and shock or vibration due to temperature gradient on a solid wall of the stack. Temperature is also available with pressure periodic or oscillation motion. The thermoacoustic effect occurs from the thermal dissipation by heat transfer between the oscillating of liquid at the surface of solid. (Symko, 2006).

The increasing interest in thermoacoustics can be one reason for its potential to protect and conserve the environment. Energy conversion from heat to electricity using a sound is one of a method in thermoacoustic heat engine technology. Then, using existing technologies, the conversion of sound into electricity has used piezoelectric devices that are compressed under pressure, including sound waves, and convert this pressure into electricity. Piezo means pressure or squeezing.

Another reason the thermoacoustic technology is free from moving parts and can be implemented with the main carrier composition thermoacoustic heat pump or heat engine. There are no moving parts in the thermoacoustic heat engine or thermoacoustic heat pump. In an example, in a cold flow tube of heat pump, no parts move except for the units which provide gas flow oscillation. Such an oscillating gas flow is only the power of the main thermoacoustic drive. In addition, it generally uses the same gas as the working fluid. This means that basic thermoacoustic medium can be used directly to move a cold pulse to implement a cooling system without moving parts.

1.3 Problem Statement

Renewable energy sources are wonderful options because they are limitless. Nowadays, energy crisis and greenhouse effects have led to the development of lots of emerging technologies that are sustainable and friendly to the environment. Thermoacoustics is a technology that can be classified as 'green-technology' as it converts thermal energy for a generator or a cooler without the use of depleted fossil fuels or harmful refrigerants. It can be integrated with sustainable and renewable energy sources (i.e solar, industrial-waste-heat) to produce power or cooling effect which are the basic needs for residential houses as well as the industries.

Thermoacoustic is a principle of science that is related to the conversion of energy in a sound wave into useful electrical power or cooling effect. This happens when the oscillatory flow of the sound wave comes into contact with solid boundaries so that the processes of heat transfer, expansion and compression take place in the fluid. Common issues with all energy transfer in the related thermoacoustic system engine in the heat-exchanger where the efficiency and effectiveness of one energy system are always relying upon the effectiveness of the heat exchanger. The biggest challenge in commercializing the thermoacoustic technology is its effectiveness that is related to, among others, the lack of data to form fundamental correlations that represent heat transfer behaviors in the oscillatory flow of the thermoacoustic phenomenon.

From the classical fluid flow and heat transfer point of view for thermoacoustic, heat transfer is very much related to the behavior of the fluid flow. In a normal steady flow condition, it is often observed that heat correlations depend on whether the flow is within the acoustic pressure-volume or geometrical properties of components. In an oscillatory type of flow caused by acoustic pressure, the classification of flow is not yet well defined. The cyclic manner of the flow introduces the harmonic wave from the hot flow and cold flow from the hot and cold heat exchangers caused by compression and expansion of heat oscillation. This phenomenon occurred by interaction on the solid surface of a stack. Researchers are yet to find a standard design in order to overcome geometrical and design issues as by right, the correlation between design and geometrical properties depends on the researchers' own standard.

Defining heat correlation is not an easy task as such, it is difficult to determine the heat correlation that can truly represent the flow condition of the desired drive ratios in thermoacoustic systems. This makes designing an efficient thermoacoustic system challenging. Heat correlation comes from a good design which consists a system which the heat can be extracted and distributed from the hot heat exchanger itself. Literature surveys found that the current practice normally has 20% to 40% of Carnot efficiency output from the thermoacoustic system. It is challenging in designing high-efficiency devices without a standard design of a system such as the standard code design in mechanical system e.g. ASME standard.

Therefore, fundamental works are needed to collect ample data for generating a heat correlation that is accurately representing the heat transfer performance of heat exchanger in oscillatory fluid flow condition of thermoacoustics. To achieve this, a comprehensive laboratory-based works and numerical models simulation need to be carried out to understand a broader perspective of the pressure-volume approach.

1.4 Research Objective

The main objective of this research is to design and analyze a thermoacoustic heat engine system. From the design approach, this study formed a standard guide algorithm of the design method. The design method is based on the theoretical formulation of the thermoacoustic heat engine. The design algorithm is a new approach to address for simple and faster way of making a new design in this field. A simulation approach is used to investigate and analyze the heat exchanger component. This study can further develop an experimental design test rig to carry out experimental work for fundamental study of analyzing a correlation between the heat and the heat transfer performance. Comprehensive laboratory-based work has been done to collect ample data to understand the correlation of acoustic sound pressure-volume due to heat transfer performance by the oscillatory flow on the thermoacoustic system.

a) To investigate the physical behavior and characteristics of geometrical and thermo fluids properties parameters in the physical system using a modelling and simulation. Modelling and simulation study on the thermoacoustic effect due to the oscillating flow and heat transfer characteristics in the system. The study was an approach to find the performance and characteristic of parameter interaction within the system.

b) To investigate the performance and parameter characteristic from heat energy to sound energy of heat and sound developed from the thermoacoustic heat engine. A performance test will be carried out by experimental work and the analysis of the results from a measurement technique of a thermoacoustic heat engine.

c) To propose a new design of thermoacoustic heat engine in a quarter-wavelength scale of standing wave as an experimental rig to harvest sound energy from heat energy as a task in thermoacoustic effect. The design will be assessed based on the waste heat phenomenon with the temperature ranged from 200 °C to 700 °C and production of sound energy in the audible range frequency. The test equipment was an approach to simulate the actual phenomenon of sound energy behavior from waste heat energy.

1.5 Scope of Study

The scope of this study involves designing, development and experimental work of the thermoacoustic heat engine with a newly design method in the thermoacoustic heat engine components development from stainless steel alloy 304, Kanthal wire and Corning Celcor - Ceramic Substrates as a material. The design method proposed as a standard design method is followed from the principles of fundamentals thermoacoustic theory. A simulation study has performed with commercial code software Ansys Computational Fluid Dynamics (CFD) and special thermoacoustic software Design Environment for Low-amplitude ThermoAcoustic Energy Conversion (Delta EC) from Los Alamos National Laboratory (LANL). Mathematical modelling and simulation on heat oscillation due to compression and expansion of gases is analysed using a MATLAB programming language software. Then a sound pressure volume and phase angle of hot and cold temperature oscillation is analysed with the same software, a MATLAB. Performance evaluations were conducted experimentally on the development of a thermoacoustic heat engine test rig at the Control, Sound and Vibration Research Laboratory, School of Manufacturing Engineering, Universiti Malaysia Perlis (UniMAP). The measurement of the experimental technique is setup using a graphical user system (GUI) with Laboratory Virtual Instrument Engineering Workbench (LabVIEW) as a measurement environment.

1.6 Research Contributions

The thesis makes several contributions to the heat oscillation due to energy harvester, which are reflected in several journals and conference papers arising from this work, as detailed in this section into several aspects such as:

a) Novelty in designing the energy harvesting technique from waste heat converted to sound energy to electrical energy using a system of thermoacoustic heat engine device. The designing is proposed by the standard flow chart for the design strategies for new development of an apparatus of thermoacoustic energy converter.

b) The development and the performance test of an experimental test rig apparatus are carried out and it is capable to simulate the actual thermoacoustic effects phenomena from a range of waste heat temperature range for automotive application within the system on energy harvester within the range of audible frequency.

c) Proposed a mathematical modelling technique to suppress heat oscillation due to energy harvester through the implementation of experimental measurement study from the mathematical modelling that have been used for new developments unit for the curtain range in waste heat temperature and the audible range of frequency.

d) Implementation of experimental work to find the frequency range within a standard audible frequency for next future development on selected a new device as linear alternator. The suitable linear alternator has been used to harvest electrical energy from the sound frequency due to audible range of frequency.

1.7 Methodology of the Study

The methodology that restricted to this research study is intended to the correlation between heat oscillation and sound frequency generated from the temperature gradient along stack. Figure 1.4 shows the overview of flow chart study on an interactive component within the thermoacoustic heat engine and heat pump system.

a) An experimental technique is conducted open and closed end type resonator and located as a stack. The system is developed to create a self-sustained oscillation from sound wave as heat oscillates as a function of standing wave. Frequency, pressure and temperature measurements are conducted on the standing wave system within the audible range frequency. The heat supplied, Th as a source to the system is in the range 150 °C to 700 °C due to hot heat exchangers. The energy harvester is measured as the conversion heat to sound with a ½" piezotronic microphones is highly accurate device and realiable for acoustic measurement. Measurements input data are logged, analysed and then developed using the Graphical User System GUI using LabVIEW environment. A special microphone from microphone is used to measure the frequency and pressure. The temperature is measured using Thermocouple type-K. The system is embedded with all sensor interfaces on circuit board fabricated in house as well for data logging system.

b) The simulation modelling of open and closed end type resonators with temperature input as main media to create sound and oscillation of heat flow as boundary conditions on stack wall is carried out. The fourth-order of Runga-Kutta integration method is used as the simulation process to evaluate a gas interaction phenomena conversion to convert heat to sound in tube thermoacoustic heat engine. The main advantage of this method is found to be its computational efficiency. Since it can estimate the effects of all parameters of geometry and material properties quickly, the present model is suitable in optimising energy harvester systems. For a better understanding on the aspects of its fundamental design, commercial code software DELTA EC is employed for the simulation process. Some characteristics or parameters in the system are analyzed in order to derive the fundamental knowledge of that an open and closed end type resonator.

c) Developments an experimental rig are needed to analyse the performance and parameter characteristic from heat energy to sound energy. A system is developed by the new design of a thermoacoustic heat engine in a quarter wavelength. Modelling for heat oscillation within the stack has to proposed . This modelling approach stand to evaluated and proven the theoretical background of the heat oscillation phenomena due to temperature at hot and cold temperature difference. Gas bucket bridget have to examined and shown in classical thermodynamics processs. This portion has shown fundmental processs occurred within acoustic and thermal interaction on astack wall. Corellation between gas parcel at hot heat exchanger and cold heat exchanger iteraction on solid medium is call fluid structure interaction have shown in Pressure Volume diagram. The phenomena is influence with stack geometrical and dimension.The work describes in this thesis involves modelling and experimental study on heat oscillation due to energy harvester. The present study is intended to the correlation between heat oscillation and sound frequency generated from the temperature gradient along stack.

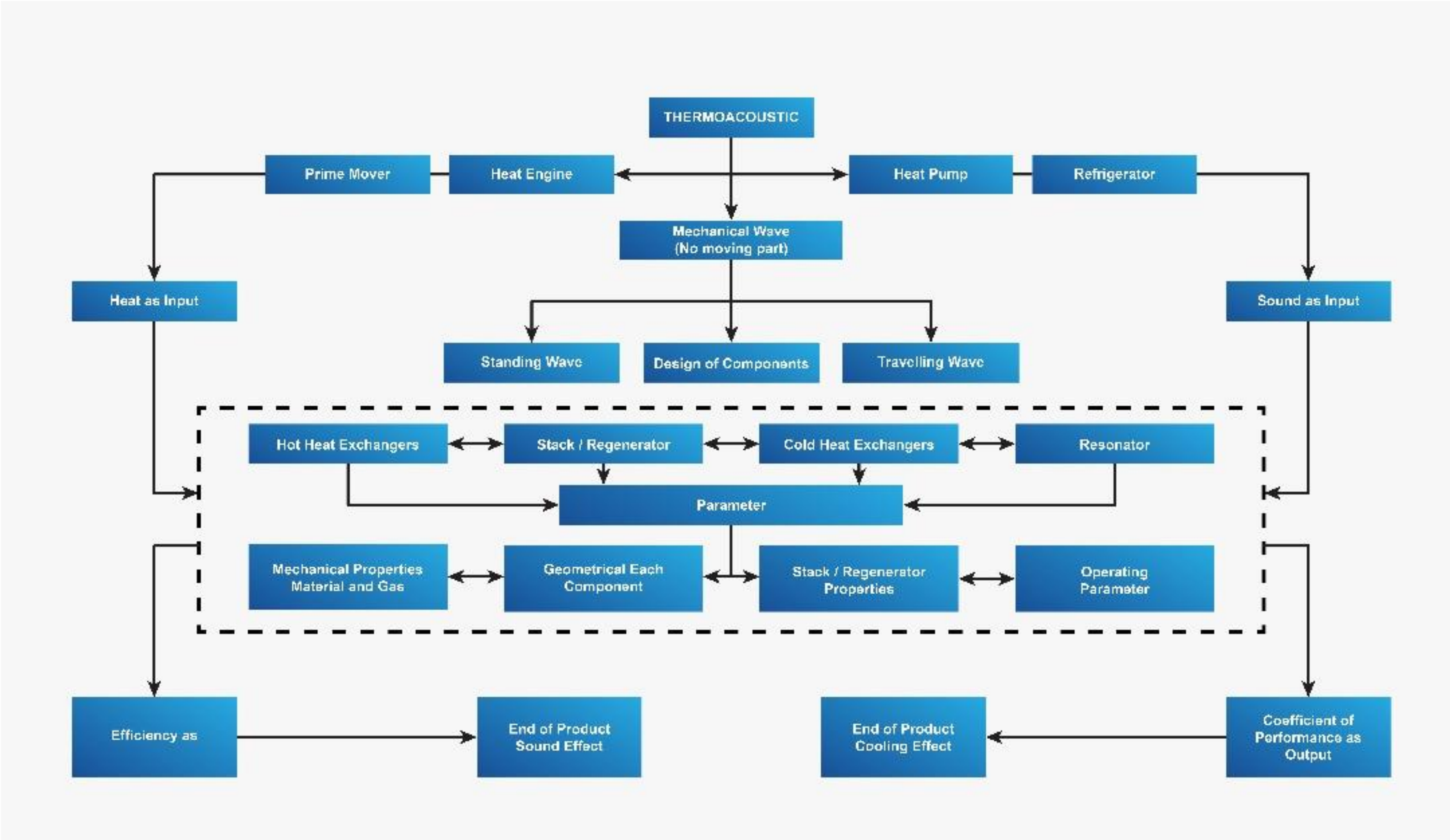

Figure 1.4 An interactive component within the thermoacoustic heat engine and refrigerator system

The fabricated devices have been made and to validate their performance, the thermoacoustic heat engine is tested with the heat supply from hot heat exchangers and several boundary conditions of the system have been made by assisting the current heat supplied to control the temperature ranges within the actual waste heat temperature. The experimental technique on thermoacoustic heat engine will be done on a test-rig that is able to resemble actual system of waste heat supplied to create a temperature gradient. M easured data from the thermoacoustic heat engine performance during the experiment will be recorded by LabVIEW commercial code software and analysed through the Mat Lab commercial code software and the results will be compared with the results determined from simulation works. Figure 1.5 below shows the basic of schematic diagram on this research study. Finally the overall research methodology strategies is concluded. The proposed research strategy in the form of a flow chart is graphically shown in Figure 1.5.

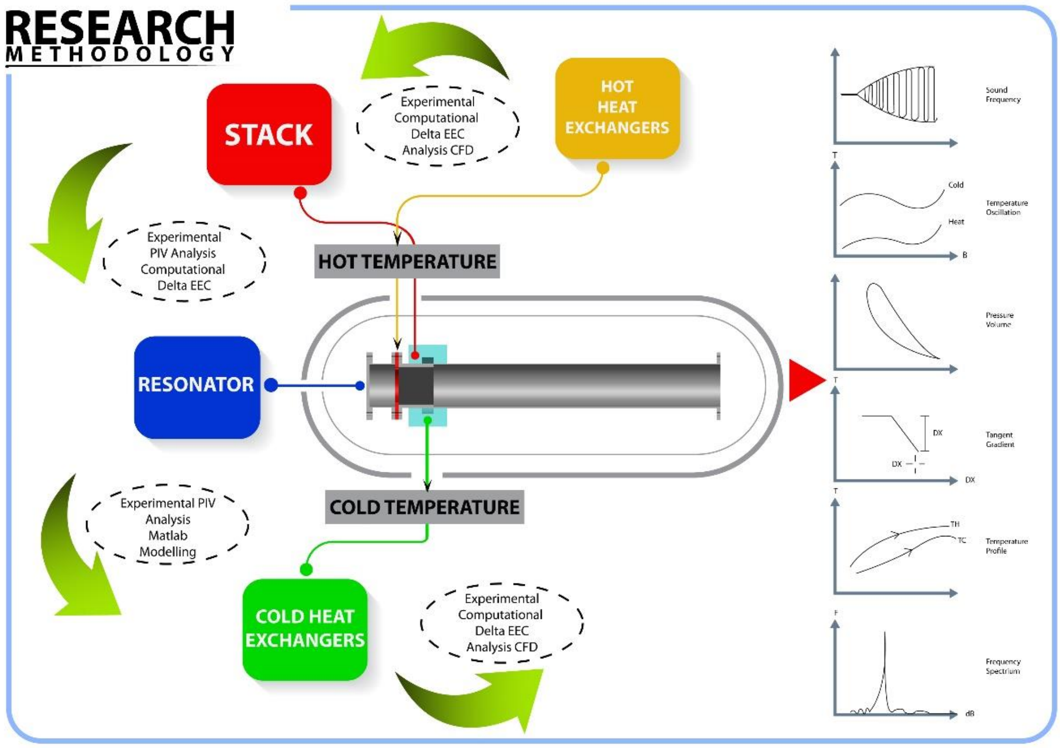

Figure 1.5 Basic schematic diagram of research methodology

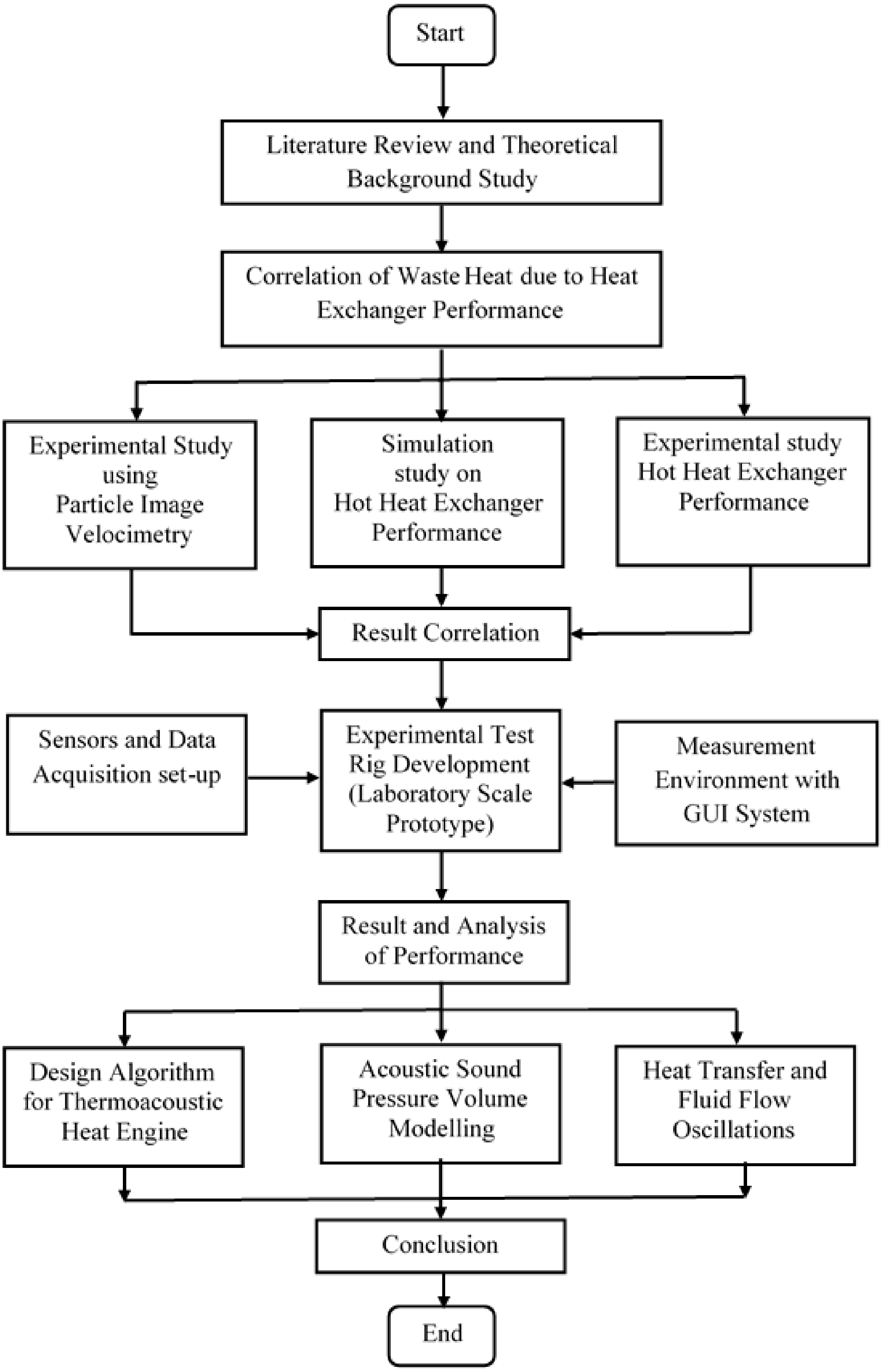

Figure 1.6 Research flowchart

1.8 Organisation of the Thesis

This thesis consists of six chapters; Introduction, Literature Review, Methodology of the study which are covered in three chapters, chapter three until chapter five; Results and Discussion and Conclusion and Future Work.

Chapter 1 is the Introduction. This chapter defines the reason this project is done. This chapter states background and overview of the project, problem statement, project objective and scope of project, layout of thesis and contribution of work.

Chapter 2 is the Literature Review. All the work in this chapter is restricted within the scope of work as stated in the first chapter. Previous projects from other researchers are also included to support the theory used in this project such as journals and thesis.

Chapter 3 is the first methodology. In fundamental design study, there is several aspects that need to be concerned with to meet the objective. Therefore, this chapter will review on choosing the operating parameter, designing the stack, resonator and heat exchanger and all the necessary calculations. This chapter also consists of the theories and studies that are related to strengthen the project. It covers the relation between thermodynamics and acoustical phenomena on the fundamental design.

Chapter 4 is the second methodology. This chapter will discuss about the modelling and simulation study involving the development of the thermoacoustic prime mover. The development of simulation model begins with the preliminary design until the experimental rig apparatus is completed. The modelling and simulation include choosing operating parameter, modelling strategy and parametric estimation.

Chapter 5 is the third methodology. This chapter shows how the experimental work is being done on the prototype development. The performance test is conducted and the prototype is used during the experiment. Properties of the prototype are also explained in this chapter.

Chapter 6 is the last chapter in this thesis which is Conclusion and future work. Overall design component and the results are concluded in this chapter. In addition, there are some recommendations stated for future studies and design improvement in Results and Discussion. The results are obtained from the experimental analysis and heat oscillation modelling study. Both results are analysed based on the primary objective and theoretical study. Tables and graphs are plotted in this chapter and the result is discussed in detail on the experimental work verified with modelling technique.

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1. **Irfan A.R**, Mohd Zarhamdy M. Z, Nor Zelawati A. and Mohd Sazli M.S. (2015). Determination Performance of Thermoacoustic Heat Engine Simulation by Delta EC Software. *Key Engineering Materials* 660, 311-316. **(Indexed by SCOPUS)**

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1. **A.R. Irfan**, M.Z.M.Zarhamdy, S.M.Sazli Saad, H.M.Hafiz, A.Azlida. (2018). Cooling effectiveness of thermoacoustic heat engine development. *AIP Conference Proceedings Publishing*, 2030, 020312-1-9. **(Indexed by SCOPUS)**

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2. **Irfan A R**, M Zarhamdy M Z.,M Sazli S, M A Asraf P,N.A Shuaib and pzlida A. (2019). Evaluation of pressure volume characteristics for thermoacoustic heat engine. *AIP Conference Proceedings Publishing*. IconGDM 2019-182

International Special Award in Exhibition

1. Special award from, "Gheorge Asachi" Technical University of IASI. *A new design of thermoacoustic energy converter-WH2E*. 7th European Exhibition of Creativity and Innovation (EUROINVENT). 14-16 May 2015, Lasi, Romania.
   Researcher: **Irfan bin Abd Rahim**, Assoc. Prof Ir Dr Mohd Zarhamdy Md Zain and Assoc. Prof Dr Norzelawati Asmuin

2. Special award from Korea Invention News in Euroinvent. *A new design of thermoacoustic energy converter-WH2E*. 7th European Exhibition of Creativity and Innovation (EUROINVENT). 14-16 May 2015, Lasi, Romania.
   Researcher: **Irfan bin Abd Rahim**, Assoc. Prof Ir Dr Mohd Zarhamdy Md Zain and Assoc. Prof Dr Norzelawati Asmuin

International Award in Exhibition

1. GOLD Award. .*A new design of thermoacoustic energy converter-WH2E*. European Exhibition of Creativity and Innovation (EUROINVENT). 14-16 May 2015, Lasi, Romania
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National Award in Exhibition

1. Silver Medal. *A New Method Energy Harvested from Waste Heat to Sound using a Linear Alternator*. CEGeoGTech and School of Manufacturing Engineering UniMAP. Malaysia Technology Expo (MTE 2017) 16-18 Feb 2017 PWTC, Kuala Lumpur, Malaysia
   Researcher: **Irfan Abd Rahim**, Assoc. Prof. Ir Dr Mohd Zarhamdy Md zain, Assoc. Prof Dr. Norzelawati Asmuin and Ir Dr. Mohd Sazli Saaad

2. Gold Medal - *A new method energy harvested from waste heat to sound using a linear Alternator.* School of Manufacturing Engineering and CEGeoGTech UniMAP. UniMAP Researcher Expo 2016.
Researcher: **Irfan Abd Rahim**, Assoc. Prof. Ir Dr Mohd Zarhamdy Md zain, Assoc. Prof Dr. Norzelawati Asmuin and Ir Dr. Mohd Sazli Saaad