THE STUDY OF WAVE DISTORTION IN A THERMOACOUSTIC SYSTEM

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This report is submitted
in fulfillment of the requirement for the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

JUNE 2021

DECLARATION

I declare that this project report entitled “The Study of Wave Distortion in The Thermoacoustic System” is the result of my own except as cited references.

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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.

Signature: ....

Name of Supervisor: TS. DR ASRIANA BINTI IBRAHIM

Date: ....

DEDICATION

To my beloved family.

Thanks to the non-stop encouragement and guide given by my honourable supervisor, Ts. Dr. Asriana Binti Ibrahim, I can complete the task successfully.

ABSTARACT

A thermoacoustic system gives a lot of benefit to the environment and the ecosystem. A thermoacoustic system helps us to reduce pollution and fully make use of the sound energy that been wasted before. Even though the thermoacoustic system is a good technology but without fully understanding how it works and the elements that affect the thermoacoustic system's efficiency, it just a waste for us. Therefore, a study of wave distortion allows us to understand the wave behaviour of the wave that been used in thermoacoustic. Besides, additional knowledge on other elements may help increase the efficiency of the thermoacoustic system. In this study, two mini test rigs of the thermoacoustic system have been made to measure wave velocity experimentally. The mini test rigs are differed by diameter and length of the resonator. We could understand the relationship between the wave velocity, diameter, and the length of the resonator from the findings. It is found that wave distortion has existed in the design of a small diameter but long resonator.

ABSTRAK

Sistem termoakustik memberi banyak manfaat kepada persekitaran dan ekosistem. Sistem termoakustik membantu kita mengurangkan pencemaran dan memanfaatkan sepenuhnya tenaga bunyi yang telah dibazirkan sebelumnya. Walaupun sistem termoakustik adalah teknologi yang baik tetapi tanpa memahami sepenuhnya cara kerjanya dan unsur-unsur yang mempengaruhi kecekapan sistem termoakustik, ia hanya sia-sia. Oleh itu, kajian penyimpangan gelombang membolehkan kita memahami tingkah laku gelombang gelombang yang telah digunakan dalam termoakustik. Selain itu, pengetahuan tambahan mengenai elemen lain dapat membantu meningkatkan kecekapan sistem termoakustik. Dalam kajian ini, dua rig ujian mini sistem termoakustik telah dibuat untuk mengukur halaju gelombang secara eksperimen. Rig ujian mini dibezakan berdasarkan diameter dan panjang resonator. Kami dapat memahami hubungan antara halaju gelombang, diameter, dan panjang resonator dari penemuan tersebut. Didapati bahawa penyimpangan gelombang telah wujud dalam reka bentuk resonator berdiameter kecil tetapi panjang.

ACKNOWLEDGEMENT

I would like to acknowledge the contribution of several people who have been influential during completing this study. I would like to thank my supervisor, Ts. Dr. Asriana binti Ibrahim for providing me tremendous support on completing this study. Her technical suggestions and eye for finer details have always been of immense help in completing this project. Ts. Dr Asriana has been a wonderful advisor in that she always encourages one to think and work independently.

Next, a big thanks to all my friends in the Mechanical Engineering department for their encouragement and support throughout my study. Finally, a special appreciation to my family supporting me during this hard time and for being understanding throughout this journey.

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CHAPTER 1

INTRODUCTION

1.1 Background

Technology gives a lot of advantages for human needs. But we forgot that technology also causes pollution to the environment and require a new type of technology that is more eco-friendly with the environment, especially in the refrigeration system. Now adays, refrigeration system used harmful gasses such as Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs). These gasses can damage our earth ozone layer and can cause global warming. A thermoacoustic refrigeration system is suitable for replacing the old system because the thermoacoustic system used inert gas as the working fluid to operate the system. The usage of inert gas is cheaper than the old refrigeration system. In the thermoacoustic system, they only used simple mechanical technology, which is easy to assemble, and maintenance compared to the old system that used complex mechanical technology (Zolpakar,2016).

The thermoacoustic refrigeration system used the acoustic energy that been provided by the thermoacoustic engine, or the acoustic driver usually loudspeaker had been used. With the support of the acoustic driver, the fundamental resonance frequency for the resonator, the working fluid usually use inert gas, had been compressed (heat up) and expanded (cool off) adiabatically by an acoustic standing wave. Then the working fluid is oscillating within the stacks. Next, the thermal interaction between the acoustic wave with the plate changed the original temperature (one-part become hot, and the other parts become cold). The temperature difference will occur between the stacks, and the heat exchanger needs to be attached at both end stacks so that the heat pump process will occur. Once the process of heat in and heat out occurred at the ends of the plates, the refrigeration system occurs (Tiwatane,2014).

The importance of studying wave characteristics in the thermoacoustic system is to improve efficiency and performance and to understand more about the wave that is suitable for use in the system. Some of the waves are not suitable to be used especially if we want to gain the high efficiency of the refrigerator in the thermoacoustic system. According to Ke, et. al, (2010) the performance of the thermoacoustic system in a practical application can be improved by increasing the amplitude of the sound wave. Other than that, another factor can help improve the performance of the thermoacoustic system. According to Poignand, et. al, (2007) optimizing the pressure velocity field in the thermoacoustic system can be improved and the efficiency of the refrigerator.

1.2 Problem Statement

Thermoacoustic is the interaction between thermal and acoustic waves that provide many eco-friendly benefits to the environment and sustainable for a cooler or generator. But, unfortunately, a lack of understanding of acoustic wave behaviour, how it works and its efficiency determination, the thermoacoustic system has not yet been used as a commercial system. Therefore, wave characteristic needs to be studied such as distortion behaviour that can affect the system performance and efficiency when the thermoacoustic refrigerators are driven at small and large amplitudes.

1.3 Objective

The Objectives of this project are as follows:

1. To evaluate the acoustic wave distortion in a mini thermoacoustic system.
2. To determine the parameters that affect acoustic wave distortion in the thermoacoustic system.

1.4 Scope of Project

The scopes of this project are:

1. The study of wave characteristic is focusing on distortion behaviour.
2. The application of a large-scale thermoacoustic test rig is for a cooling system.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, a literature review based on previous works is done to understand the basic principle and application of the thermoacoustic system. In addition, studies on the acoustic wave are also conducted to understand its characteristics that may affect the performance of the thermoacoustic system.

2.2 Thermoacoustic

In general, thermoacoustic is the reaction between acoustic wave and temperature with a variation of density and pressure. The thermoacoustic system is a system that utilizes the phenomenon of the thermoacoustic, which is mutual energy conversion phenomenon between heat and sound (Kurata,2020). The cold energy and electrical energy can be pulled out from the reconversion once the thermal energy had been converting into sound energy. Based on the thermoacoustic system, the cooling facilities, air conditioner, and electrical generator can be powered by the unused thermal energy that been wasted before, such as factory exhaust heat and solar light.

A study claimed that the thermoacoustic phenomena are the solid-fluid interaction which involves the capability of the heat pumping mechanism of working fluid usually used inert gas of either generating acoustical work or inducing a cooling effect Zolpakar, et. al, (2016). Thus, acoustic work involves the process of heat movement from a lower temperature reservoir to a high-temperature reservoir.

2.3 Thermoacoustic Application

A thermoacoustic system can be applied to high temperature (generator) or low temperature (cooler) applications. According to a study stated there are two applications for the thermoacoustic system, which are the thermoacoustic engine and the thermoacoustic refrigerator (Kujerak, 2018). The thermoacoustic engine is the system that utilizing the heat flowing from high-temperature sources to low-temperature sources to generate acoustic power. In contrast, the thermoacoustic refrigerator is the system that transfers heat from low-temperature sources to high-temperature sources by absorbing acoustic power.

Biwa (2012) stated the thermoacoustic engine is the system that supplied heat from acoustic power generates from the prime mover based on the thermoacoustic oscillation. Biwa (2012) and Tijani (2011) claimed standing wave thermoacoustic engine is unsuitable for a thermoacoustic engine because it has a lower thermal efficiency of converting heat supplied into acoustic power than a travelling wave thermoacoustic engine. The situation can be seen through the data that shown travelling wave has 32% of thermal efficiency while 49% Carnot efficiency.

They also stated that the main component for the thermoacoustic engine is the stack for the standing wave and regenerator for the travelling wave. Both are the same material which is the porous material that consists of narrow flow channels in which energy conversion from Q (heat flow) to I (workflow) occurs. The usage of this porous material is to enhance the thermal contact of the gas with solid walls. The interaction between the acoustic wave with the solid walls is the elements for the thermoacoustic engines. As shown in Figure 2.1, the Stirling engine is the same as the travelling wave thermoacoustic engine.

According to Tijani (2002), the thermoacoustic refrigeration system is the system that produces cooling power by using the sound wave. As shown in Figure 2.2, the thermoacoustic refrigeration system consists of several main components that help the system undergoes the cooling process very well. The components consist of an acoustic driver, resonator, a stack, the heat exchanger and working fluid usually used air as the working fluid in the system. The heat pump process had been generated at the stack which is occurred due to thermal interaction between sound and the surface of the stack. Tiwatane (2014) explained that the refrigerator occurred once the presence of many stacks which a part is heated and another part been cooled had been atop each other, placed of an optimal length in the optimal area of the tube and then been attach heat exchangers to get the heat in and heat out at the end of the plates. To increase the efficiency of the refrigerator system for the thermoacoustic system, we must increase the number of stacks that been used in the system based on Tiwatane’s (2014) explanation.

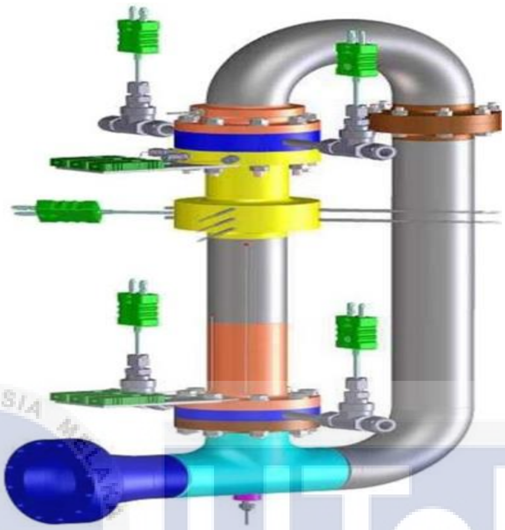

Figure 2.1: The Stirling engine (Tijani,2011)

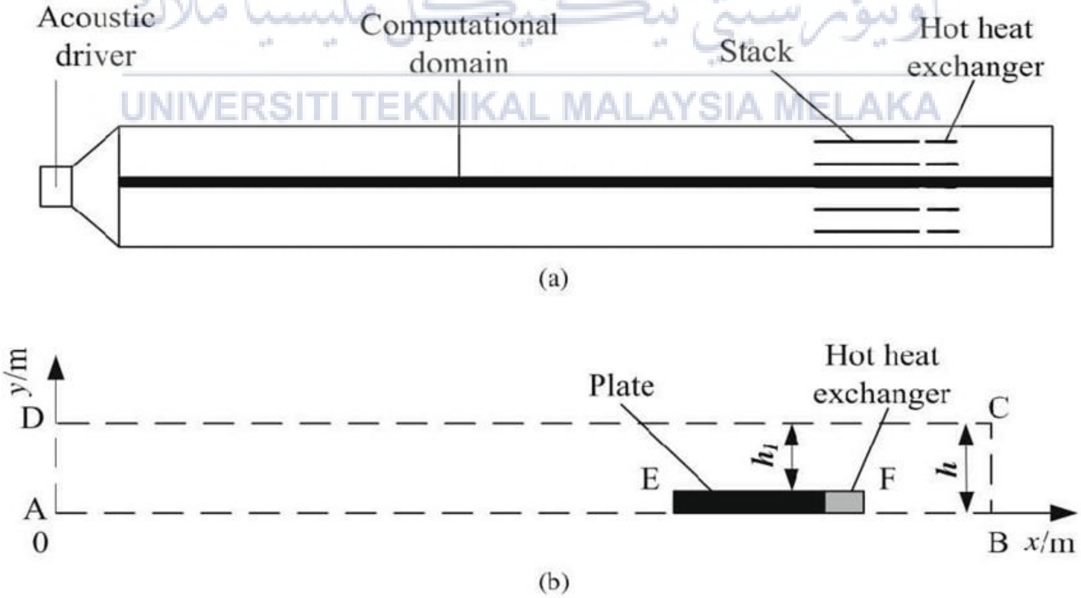

Figure 2. 2: The schematic diagram for the model of the thermoacoustic system. The dark domain is the computation domain shown in magnified in (b). (Ke et al, 2010)

2.4 Thermoacoustic System

This chapter explains the components that involve in the thermoacoustic system. There are a few main components that need in the thermoacoustic system, especially in the refrigerator. These main components may affect the efficiency of the thermoacoustic system, especially the results during running the experiment. According to Zolpakar et. al, (2016), the main components that are essential in the thermoacoustic system are the stack that been used in the system, working fluid, resonator, frequency, and average pressure. When the working fluid in the system hit the stack, the stack will act as the temporary storage for the heat inside the working fluid during the final stage of the compression (pressure antinode) or expansion (pressure node). So that the temperature of the system will decrease during the experiment due to heat transfer from the working fluid to the stack. The more the number of stacks in the system, the more the heat transfer occurred, and the temperature of the system will decrease.

Figure 2.4 show the geometries of the stack that had been used in the thermoacoustic system. The geometry of the stack may affect the efficiency of the heat transfer. When the separate gap between the solid wall decreases, the thermal boundary layer will increase and the efficiency of the thermoacoustic system will increase.

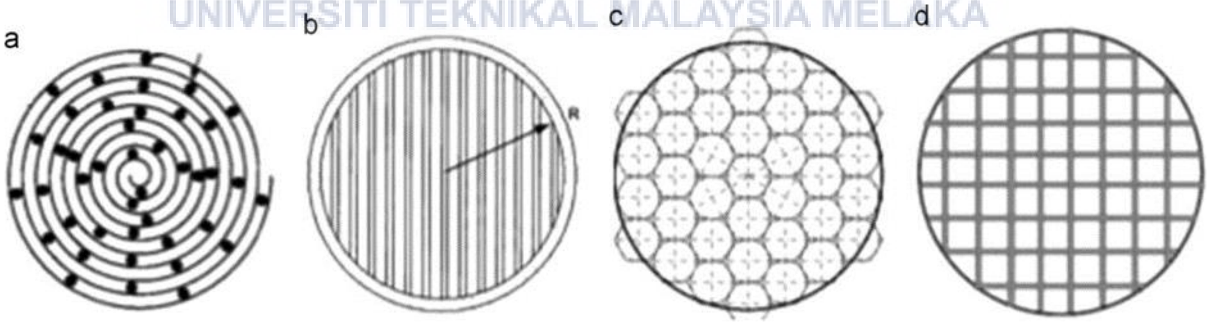

Figure 2.3: Different stack geometries utilized in the previous studies (a) spiral (b) parallel plate (c) honeycomb and (d) corning celcor. (Zolpakar et al. 2016)

According to Babu, et. al, (2017), the amount of heat produced is predominantly dependent on the material properties of the stack, such as the thermal conductivity, heat carrying capacity, the porosity, and the length of the stack. The position of the stack in the resonator also decides the amount of refrigerant that can be obtained for the thermoacoustic system. Other than that, the design of the stack also decides the amount of refrigerant that can be obtained for the thermoacoustic system. The honeycomb ceramic stack as shown in Figure 2.4, is the recommended design for the stack according to Babu, et. al, (2017) compared to the other design of the stack. This is because the material that been used is ceramic which is a good heat insulator and the shape of the honeycomb allow the wave to travel through smoothly. But according to Alamir, et. al (2019), the best material that can be used in a thermoacoustic system is steel wool. This is because the steel wool stacks had the best performance and the maximum cooling power compared to the honeycomb ceramic stack, as shown in Figure 2.4.

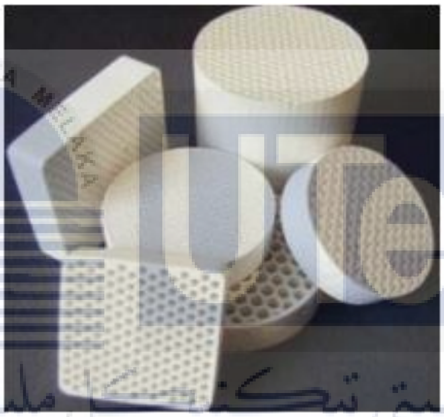

Figure 2.4: The honeycomb ceramic stack. (Babu, et. al, 2017)

Working fluid is the components that been produce inside the thermoacoustic system by the acoustic driver. There are a few types of working fluid that can be used in the thermoacoustic system. According to Kajurek, et. al, (2018), the working fluid that suitable to be used in the thermoacoustic system is the standing wave and air. Other than that, travelling wave also had been used as the working fluid in the thermoacoustic system. According to Sharify, et. al, (2017), the travelling wave also can be used as the working fluid in the thermoacoustic system. According to Tasnim, et. al, (2012), helium and xenon also can be used as the working fluid for the thermoacoustic system because they also part of inert gas. We know that all the inert gasses can be used as the working fluid for the thermoacoustic refrigeration system. Alamir, et. al (2019) also agreed with a study Tasnim, et. al (2012) about the usage of helium gas as the working fluid for the thermoacoustic system.

The next component that been used in the thermoacoustic system is the resonator. According to Babu, et. al (2017), the resonator may be of a half-wavelength type and quarter-wavelength type and with or without buffer volume of various geometries. The resonator is placed in the system where the high intensity of sound wave from the loudspeaker travels inside it. The cooling and heating process are happened at the end of the resonator due to the interaction between the stack and the waves in the resonator. Figure 2.5 shows the type of resonator that had been used in the thermoacoustic system. In the experiment that had been conducted by Johari, et. al (2019), a quarter wavelength resonator has been used and the been attached to a loudspeaker that acts as the acoustic driver. The frequency and pressure in the thermoacoustic system are affected by the acoustic driver of the system.

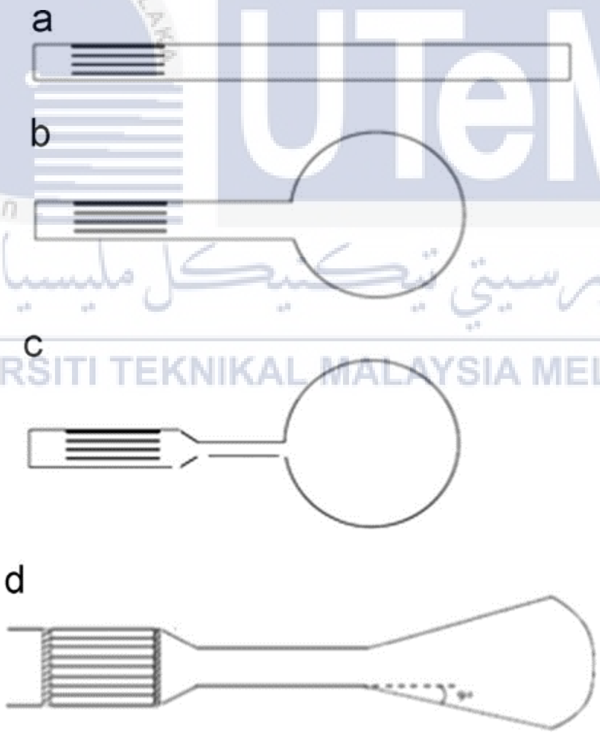

Figure 2.5: Types of resonators:(a) half wavelength (b) quarter wavelength with sphere buffer volume (c) two diameter of a resonator with sphere buffer volume and (d) two diameters of a resonator with conical buffer volume. (Zolpakar, et. al, 2016)

According to Agarwal, et. al, (2016), other components need to be used in the thermoacoustic system to increase the efficiency and performance of the system. The components that need to be used are the heat exchanger and the alternator. The function of using the heat exchanger is to keep the temperature gradient along with the stack higher than the critical temperature gradient needed to maintain the thermoacoustic effect. According to Babu, et. al (2017), the heat exchanger needs to be placed on the stack at either end of the stack. This is because the position of the heat at the end of the stack enables the heat transfer to occur from the stack ends. Even the optimal design of the stack is essential to get a maximum difference in temperature, but the presence of heat exchanger will help to increase the efficiency of the thermoacoustic system. Figure 2.5 show the heat exchanger that been used in the thermoacoustic system. The linear alternator is to increase the complexity of the design, but it also increases the cost to fabricate the thermoacoustic system. There still no cost-efficient linear alternator for the low acoustic impedance that available in the market.

Figure 2.6: The heat exchanger that been used in the thermoacoustic system. (Agarwal, et. al, 2016)

According to Avent, et. al (2015), thermoacoustic can be used as the energy harvesting system for the application of the thermoacoustic system. The critical temperature gradient that been produced in the system can be used to produce powerful acoustic pressure waves if it been fully utilized, and it can be the main key to help the thermoacoustic in energy harvesting system. The temperature gradient that occurred between the stacks or regenerator can be improved by using the mechanism for coupling a thermoacoustic prime mover with electromagnetic harvester and the piezoelectric transducer materials, as shown in Figure

2.7(a). We know that the piezoelectric transducer materials can offer the potential to enhance the energy density attained beyond that possible with linear alternators. The critical temperature gradient is the gradient through the length of the stack in the direction of acoustic wave propagation. The above part will function as a prime mover or engine, and for the below part, it will function as a refrigerator or heat pump has been shown in Figure 2.7(a).

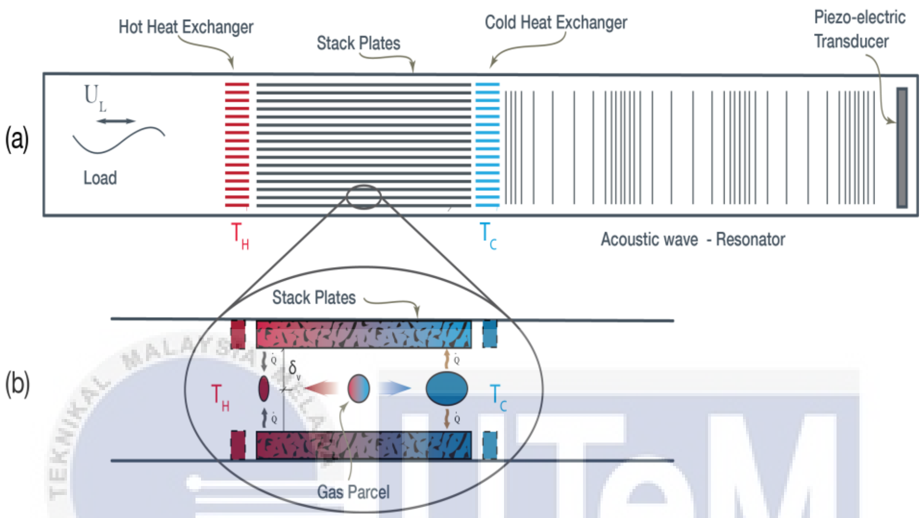

Figure 2.7: (a) The schematic diagram of a thermoacoustic energy harvester and (b) the expended view of the stack plates. (Avent, et. al, 2015)

2.5 Standing Wave in Thermoacoustic System

According to Babu, et. al (2017), the standing wave has been created due to the interaction between the reflected wave with the original wave in the constructive interference in which both waves are in the same phase, and the incident occurs in the closed medium. The reflected wave occurs due to the sound wave of pre-set frequency that been sent into the resonator has been reflected due to the closed on the other side. Kurata (2020) stated that the standing wave is the wave that undergoes the self-excited vibration at the same mode.

While for the thermoacoustic system, Kurata (2020) stated the standing wave is the sound wave that undergoes the self-excited vibration at the same mode and the heat exchange in the prime mover (PM) inside the thermoacoustic system. At the higher mode, the superposing of the sound wave had been changed from the fundamental mode to the system resonating. According to Babu, et. al (2017), the thermoacoustic effect can be seen when the sound wave from the acoustic driver is passed through a resonator at a particular frequency, the pressure pulsation forms a standing wave. This causes the oscillatory motion of the gas in the resonator along the axial direction. The combination of the pressure pulsations and the oscillatory motion of the gas inside the tube causes the heat transfer to occur. The thermal contact with the stationary surface, which is the stack, can cause the thermoacoustic effect.

According to Kang (2010), a standing wave is the components acting as the amplifier of the acoustic intensity in the thermoacoustic system. Based on the statements above, we can understand that the acoustic wave undergoes the self-excited vibration to amplify the acoustic intensity and increase the pressure inside the system. The acoustic wave then had been changed to the heat energy so that the heat energy will heat up the solid boundary (stack). One part of the stack had been heating up, and the other had been cooled, heat transferred had been occurring inside the system, and the system will produce a refrigeration system. (Allesina, 2014).

A standing wave is not suitable to be used in the thermoacoustic heat engine because of the properties of the standing wave, which simultaneously undergo compression and heating process and expansion and cooling process. This can be seen in Figure 2.8 that the standing wave graph shows that the pressures are directly proportional to the displacement. The processes are not contributing to energy conservation as heat engine (prime mover) (Biwa,2012). Meanwhile, those processes are suitable in thermoacoustic refrigeration system with the presence of the stacks in the system (Tiwatane,2014)

2.6 Acoustic Wave

According to Borg (1981), the sound is a special feature for the acoustic environment. The sound has well defined as the physical concept. The sound can be wanted or unwanted in our daily life. The unwanted sound is the definition of noise. An example of noise, as we can easily see in our daily life, is the loud voice from the vehicle or the sound that is disturbing our sleep. According to Borg (1981), sound has a great capacity to bring information or to interfere with the interchange of information. The sound also can be neutral and about its own presence.

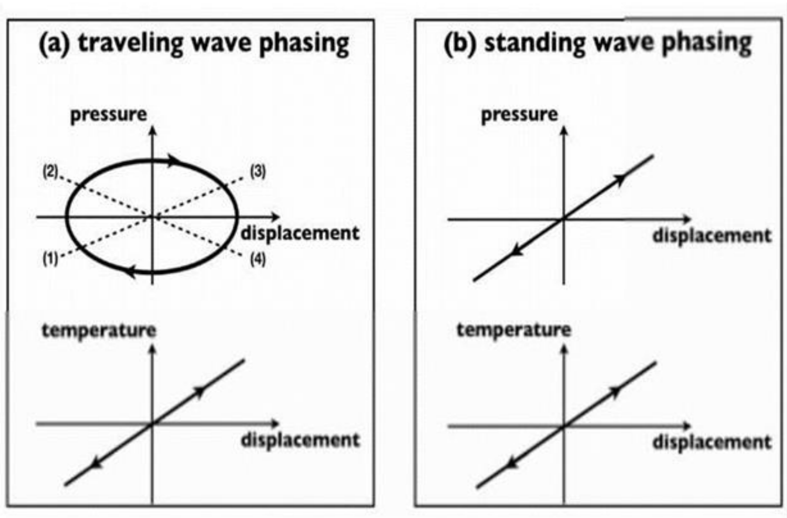

Figure 2.8: The difference between the travelling wave phasing and standing wave phasing in the pressure vs displacement graph and temperature vs displacement graph. (Biwa, 2012)

According to Vellekoop, et. al (1998), the acoustic wave has been used in the sensor application. The delay line devices, where a transmitting and a receiving interdigital transducer are realized on a piezoelectric substrate, is the common structure used. The acoustic wave has been used in the sensor because the acoustic wave devices offer high sensitivity. They are small, and they can be realized using planar production technology, allowing a low fabrication process. Other than that, the acoustic wave device has a good interaction with the outside parameter such as wave velocity and damping. The example is the adsorption of mass on the propagation path of the wave (chemical sensing in fluid), the entraining of viscosity and density) or an electric field (sensing the strength of the field).

According to the Grate, et. al (1993), the microsensors that using the acoustic wave is a very versatile class of sensors. This is because the microsensor that uses acoustic wave is highly sensitive to the surface mass changes, have many applications as chemical sensors and they can determine a variety of other media in contact with their surface, including liquid density, liquid viscosity, polymer modulus, and electrical conductivity.

An example of the sensor that used acoustic wave is the thickness-shear mode (TSM), surface acoustic wave (SAW), flexural plate wave (FPW) and acoustic plate mode (APM). The illustration view of the structures device for thickness-shear mode (TSM), surface acoustic wave (SAW), flexural plate wave (FPW), and acoustic plate mode (APM) are being shown in Figure 2.9 below, and the acoustic wave as shown in Figure 2.10. Although these all sensors as shown in Figure 2.9, use piezoelectric substrates, piezoelectricity is not the only mean for generating an acoustic wave. The acoustic wave can be generated by the magnetic, electricity and photothermal process. The characteristic makes the acoustic sensor capable of being used in a large area, and it safe to be used instead for only the physical properties.

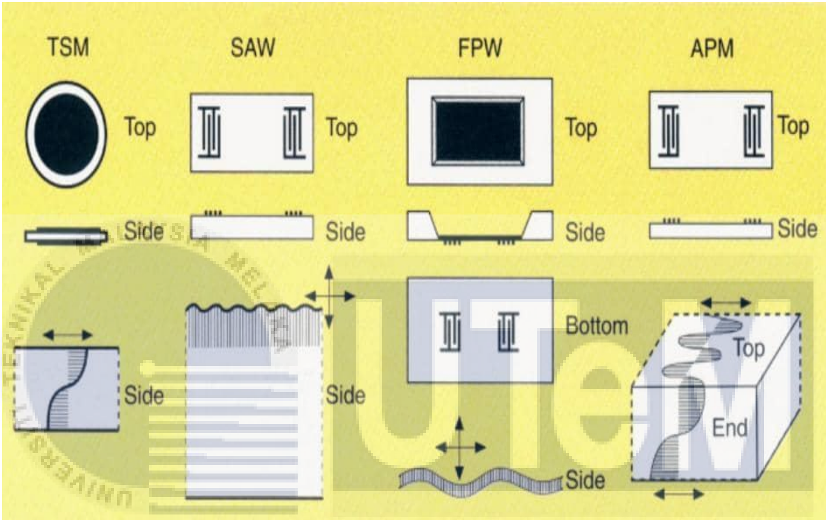

Figure 2.9: The illustration view of the structures device for thickness-shear mode (TSM), surface acoustic wave (SAW), flexural plate wave (FPW) and acoustic plate mode (APM) (Vellekoop, et. al, 1998)

According to Drafts, B. (2001), the acoustic wave application can be seen in the telecommunications industry, which is it is used surface acoustic wave (SAW) devices. The surface acoustic wave (SAW) act as the bandpass filter in the transceiver electronics. Next, the application of the acoustic wave can be seen in the automotive application, which is torque and tire pressure sensor, for the medical application, which can be seen in biosensors and for industry and commercial application we can see in the vapor, humidity, temperature, and mass sensors.

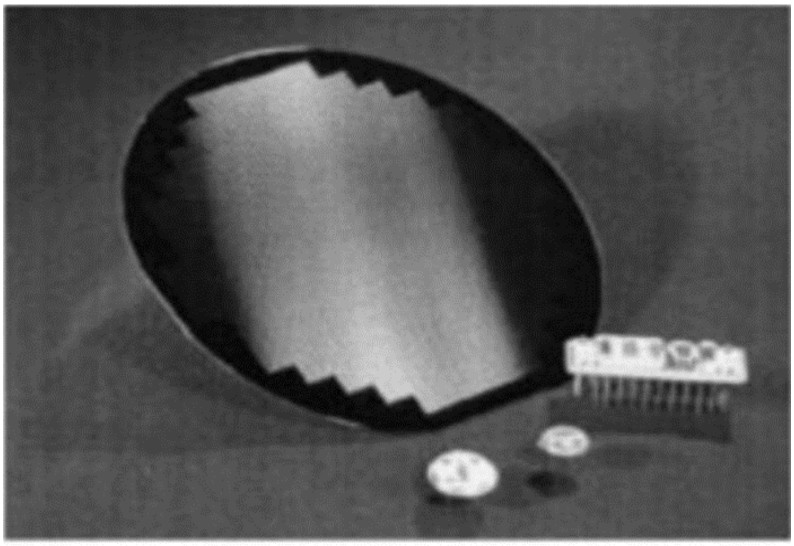

Figure 2.10: The acoustic wave sensor. (Drafts, B., 2001)

The competitively priced, inherently rugged, very sensitive, and intrinsically reliable make the acoustic wave sensor has higher demand in commercial usage. Acoustic wave sensor becomes famous because they utilize the mechanical and acoustic wave as their sensing mechanism. As the acoustic wave propagation through or on the surface of the material, any changes in the characteristics of the propagation path affect the velocity and /or the amplitude of the wave. This change can be monitored by measuring the frequency or the phase characteristics of the sensor. It also can be correlated to the corresponding physical quantity that is measured.

The surface acoustic wave (SAW) sensor mostly relies on the mass sensitivity of the sensor in conjunction with the chemically selective coating that absorbs the vapor of interest, resulting in an increased mass loading of the surface acoustic wave (SAW) sensor. The example of the surface acoustic wave (SAW) application can be seen in the surface acoustic wave (SAW) chemical vapor analyser. Figure 2.11 show the commercially available surface acoustic wave (SAW) chemical vapor analyser.

Figure 2.11: The chemical vapor analyser. (Drafts, B., 2001)

2.6.1 Reflection

The wave undergoes reflection when it hit or interact with the solid body. Only two types of waves can be propagating in an elastic body: longitudinal wave and shear wave. The particle motion is either parallel or perpendicular to the wave normal depending on whether a dilatational wave or called the shear wave. (Stoll, et. al, 1981). The main factor for the reflection of the wave is the angle of the incidence for the generating wave. When the incidence angle of the wave is bigger than the critical angle, the wave will become parallel to the interface and no longer propagates. This phenomenon can be seen in Figure 2.13 the reflection of the wave.

According to Yang, et. al (2018), the wave reflection is suitable to be used in dike detection. The seismic reflection wave method is the method that used wave reflection, and its application is good in continental oil, gas exploration, ocean survey, and it could measure accurately determine the depth and morphology of the interface. Yang, et. al (2018) also stated that the seismic reflection wave method capable of detecting the underwater position and thickness of the thin sand body accurately under the shallow water delta of Gaotaizi oil field in Daqing, China.

Other than that, the application of the wave reflection can be seen in the monitor the setting of cement-based materials. According to Öztürk, et. al (2006), the application of the reflection of wave can be used to monitor the hydration process of early-age cement-based materials throughout their setting and hardening. The ultrasonic wave reflection technique that used the principle of wave reflection shows a good result in monitoring the setting of cement-based materials and suitable to be used to monitor the stiffening of cement pastes accurately.

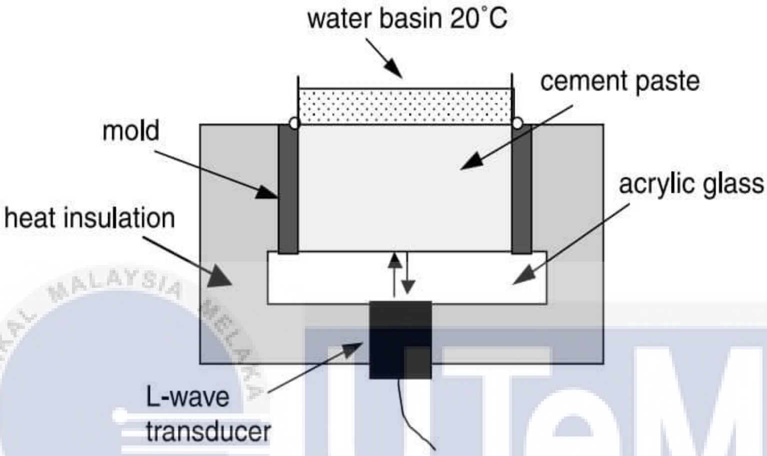

Figure 2.12: The schematic diagram of the wave reflection apparatus. (Öztürk, et. al, 2006)

According to Öztürk, et. al (2006), that the wave reflection apparatus, as shown in Figure 2.12, is suitable to be used for monitoring the stiffening of cement pastes accurately. The data that been produce by the wave reflection apparatus is correlated to the mechanical and chemical properties of the specimens, which is the cement paste. The L-wave pulse reflection from the surface of the early-age cement-base material is measured during the first 12 hours after mixing. The tests are performed using the wave reflection apparatus on the cement paste specimens since the setting process itself is unaffected by the aggregates. The role of the aggregates become more important when the hardening of concrete is investigated. The test specimen is cured under the isothermal condition at a constant temperature of 20 degree Celsius. To eliminate the influence of the ambient relative humidity on the result of the investigate, the specimen has been kept under sealed condition throughout the duration of the testing.

2.6.2 Refraction

According to Gerjuoy, E. (1948), the refraction of wave occurs when the wave pass undergoes two different mediums with different density. After it goes out from the medium that has a higher density, the velocity of the wave will reduce (loss to the medium due to high density). This phenomenon can be seen in Figure 2.13, the difference between the refraction and reflection of the wave. In Figure 2.13 also we can see that the wave moves from lower density which air, to higher density which water, and undergoes reflection and refraction at the same time.

The refraction of the wave has been used in the sensor application. According to Coccia, et. al (2010), the application of the refraction of the wave has been used in the determination of 1-D shear wave velocity in a landslide area. The Refraction Microtremor (ReMi) that used refraction of wave method has been used on a slope that affected by or prone to land sliding with the presence of lateral lithological heterogeneities and irregular topography to investigate the presence of directional variation in soil properties. A Refraction Microtremor (ReMi) has been used in this investigation due to the stability of the data acquisitions and the reliability of the results in irregular landslide terrain.

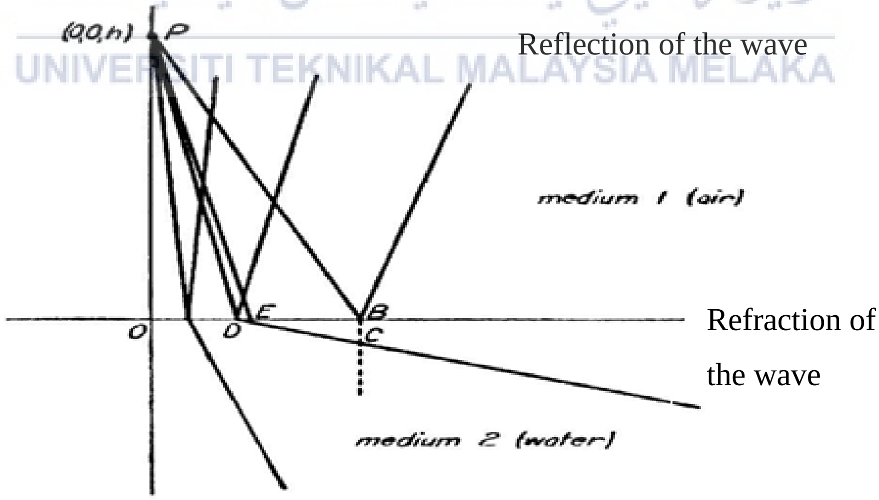

Figure 2.13: The reflection and refraction of the wave. (Gerjuoy, E.,1948)

2.6.3 Diffraction

The wave may undergo diffraction due to the surrounding. Some of the energy inside the wave may lose to the surroundings. Not only the energy, but velocity and the pressure of the wave also may lose to the surrounding. According to Dalrymple, et. al (1984), the wave field will diffract and attenuate at the place where have higher energy dissipation, such as at the bottom of the water column or throughout the water column, even though the diffraction of the wave seems not good but there some advantage that ca n be taken from the diffraction of the wave in our daily life. Pierce, A. D. (1974) explain the usage of wave diffraction around the corners and over the wide barriers.

According to Smartt, et. al (1975), the application of diffraction of wave can be seen in the sensor application. The sensor that used the diffraction of the wave is the point-diffraction interferometer (PDI). The point-diffraction interferometer is an interferometer for measuring phase variations in which the reference wave is produced by a point discontinuity in the path of the beam. The principle of the point-diffraction interferometer has been shown in Figure 2.14, which is the incident wave entered inside the point-diffraction interferometer undergoes diffraction after faced the absorbing film and producing the transmitted wave and reference wave.

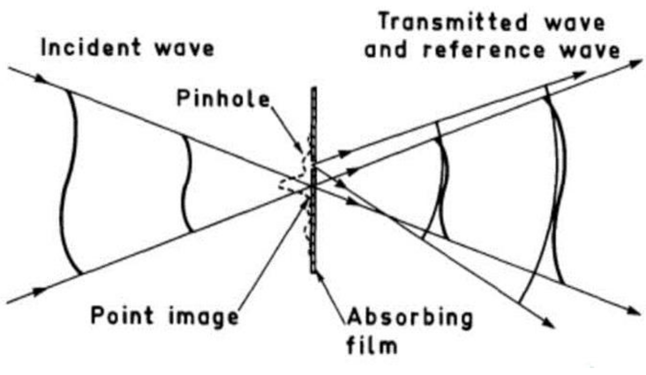

Figure 2.14: The principle of the point-diffraction interferometer. An incident wave, attenuated by the absorbing film at its focal plane, interferes with a spherical wave diffracted by a discontinuity in the film. (Smartt, et. al, 1975)

2.7 Test Rig for the Thermoacoustic System

This subchapter will explain the test rig that been used in a previous study in the thermoacoustic system. The purpose of doing this test rig is to get more understanding about the thermoacoustic system and to improve the performance of the refrigerator in the thermoacoustic system. Figure 2.15 shows the test rig that has in FKM laboratory, UTeM and Figure 2.16 shows that the other test rig that used K- type of the thermocouple as apparatus to check the temperature inside the test rig during the experiment be run. The test rig that shown in Figure 2.15 and Figure 2.16 are the test rig that been use standing wave as their working fluid in the thermoacoustic system.

There is another working fluid that can be used in the thermoacoustic system except for standing wave in the thermoacoustic system. Travelling wave also can be used as the working fluid in the thermoacoustic system and the schematic diagram for this experiment has been shown in Figure 2.17.

Figure 2.15: Thermoacoustic actual test rig at FKM laboratory, UTeM (Johari, et. al, 2019)

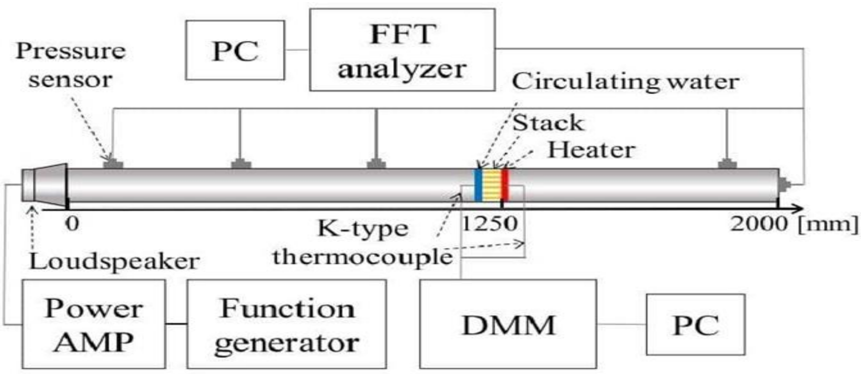

Figure 2.16: The test rig that uses the K- type thermocouple. (Kurata, et. al, 2020)

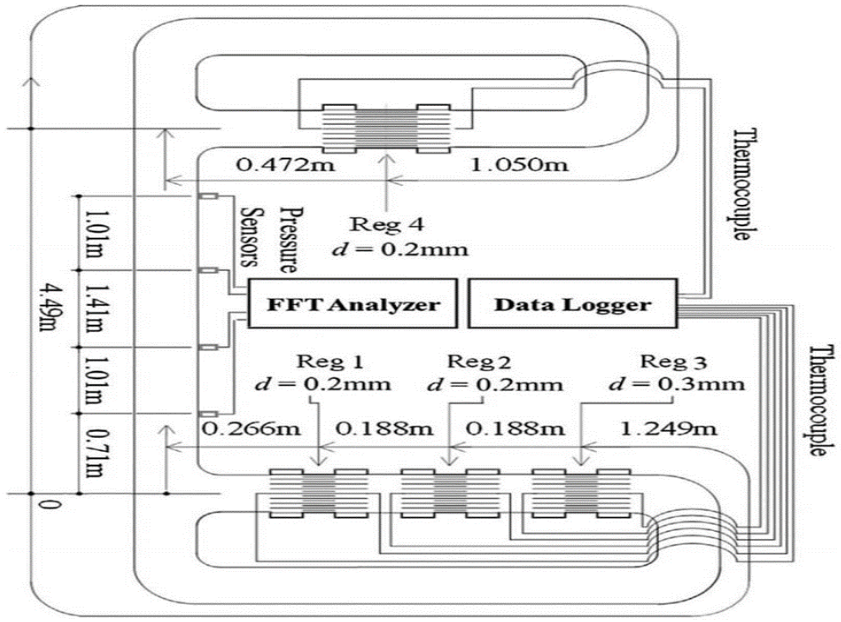

Figure 2.17: Schematic diagram of the experimental apparatus for the thermoacoustic system that used traveling wave as their working fluid. (Sharify, et. al, 2017)

According to Setiawan, et. al, (2010) the simplest resonator for thermoacoustic refrigeration is a straight tube with one end closed and the other is open to which the acoustic driver is coupled, forming a quarter-wavelength resonator tube. In this case, only one pressure antinode can be seen, and the stack has been placed near to it. Otherwise, if the half-wavelength resonator tube at which ends are closed, the two-pressure antinode will produce at both closed-end. If the two stacks have been placed neatly, the pressure antinodes, the two cooling points and two heating points will produce. The heat flow occurs in the opposite direction regarded to the stacks, which basically give one cooling region in the middle of the resonator tube, which has been shown in Figure 2.18.

According to Kharismawati, I. (2017), the usage of the Polyvinyl Chloride (PVC) in the thermoacoustic capable of increasing the efficiency of the thermoacoustic system. The meaning of the usage of the PVC in the thermoacoustic is the usage of PVC as the resonator and the stack for the system. The temperature for the thermoacoustic system that uses the PVC can be obtained 18.5 degree Celsius in the cold tendon, while for the thermoacoustic system that used stainless application obtained 88.6 K. Type of material that been used for the resonator and the stack give huge effect to the thermoacoustic system. Other than that, the position of the stack is important because the stack is the main element that helps to reduce the temperature around them. The smaller the distance between the stacks, the better the temperature reduction. Figure 2.19 show the position of the stack in the thermoacoustic system.

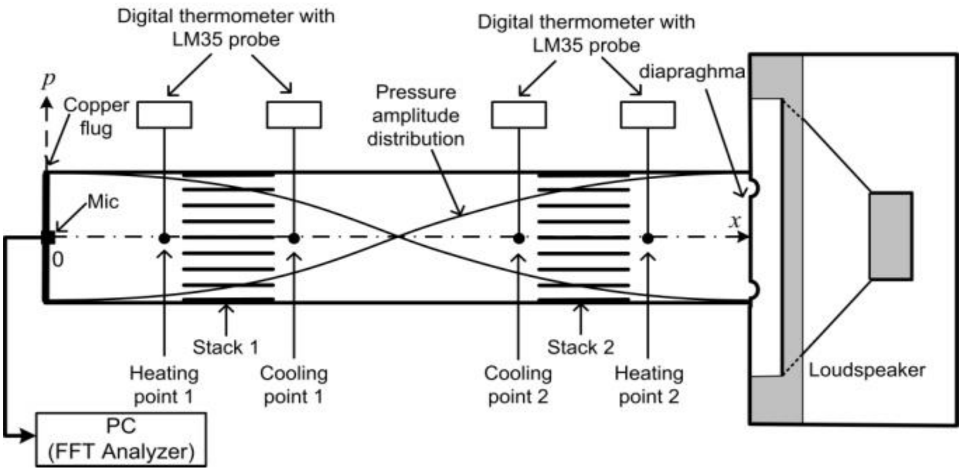

Figure 2.18: The schematic diagram of the thermoacoustic cooling system with two stacks in a half-wavelength resonator tube. (Setiawan, et. al, (2010)

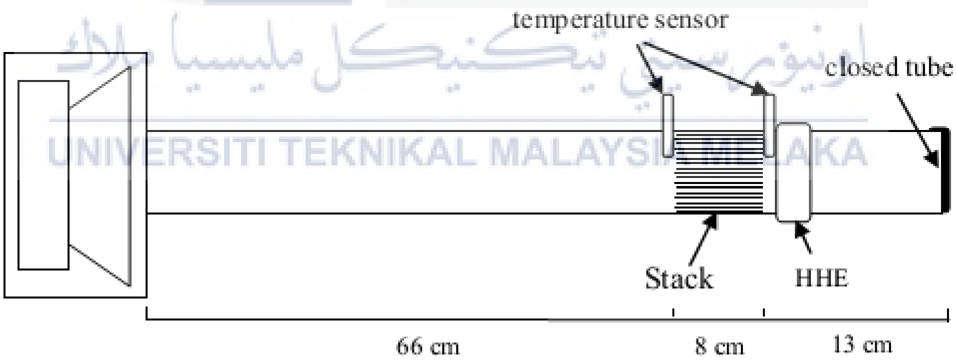

Figure 2.19: The position of the stacks in the thermoacoustic system. (Kharismawati, I., 2017)

Instead of using the straight tube for the resonator has been shown in Figure 2.17, there is another design that can be used in the thermoacoustic system. According to Li, et. al, (2013), the shape of the resonator is important in the thermoacoustic system. Even though there is a difference in the shape of the resonator, but the shape of the resonator must be able the support the main parameter that been examined in the investigation. A convection-driven-T-shaped had been used in the standing wave thermoacoustic system. The parameters that wanted to be examined for using a convection-driven-T-shaped are the inlet flow velocity, heater temperature and the heats source location. Figure 2.20 shows a convection-driven T shaped.

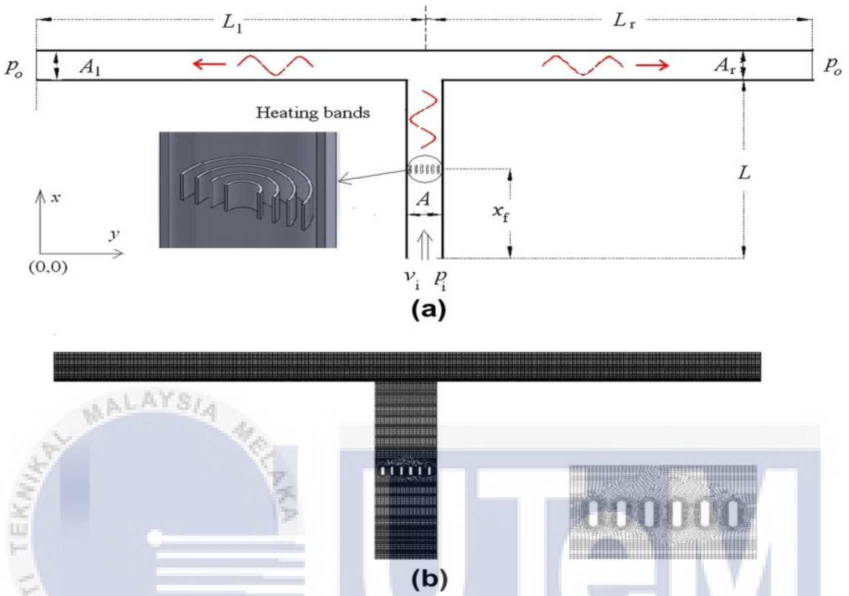

Figure 2.20: The schematic diagram of a convection-driven-T-shaped standing wave thermoacoustic system. (Li, et. al, 2013)

The sound velocity is also a parameter that can be used in the thermoacoustic design system. Most of the test rig is not purposely been fabricated to check the velocity of the wave inside the resonator. But there is a test rig that sensitive to velocity, and its application is for the premixed combustor. It is not to measure the thermoacoustic refrigeration system, but we put it here as the reference for the application of the velocity in the thermoacoustic system. According to Emmert, et. al, (2017) the application of the velocity in the thermoacoustic system can be seen in the premixed combustion test rig, as shown in Figure 2.21.

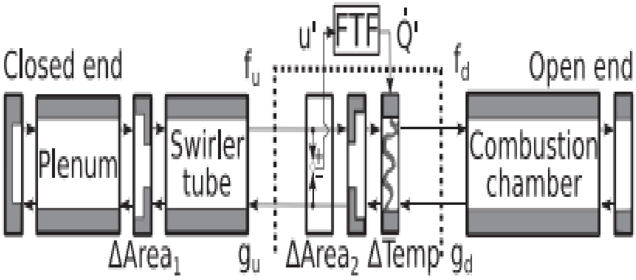

Figure 2.21: The schematic diagram of the premixed combustion test rig network model. (Emmert, et. al, 2017)

A study has been done by Alamir, et. al, (2019), to improve the efficiency of the thermoacoustic system by varying the stack geometric parameters. The parameters influence the resonance frequency of a standing wave in a thermoacoustic refrigerator. According to the study, the resonance frequency in the standing wave gives the highest performances for the thermoacoustic refrigerator. This is because the propagating amplitude pressure and the temperature difference across the stack are maximum at this frequency for the same amount of acoustic input power. The experimental setup for this study has been shown in Figure 2.22 and Figure 2.23.

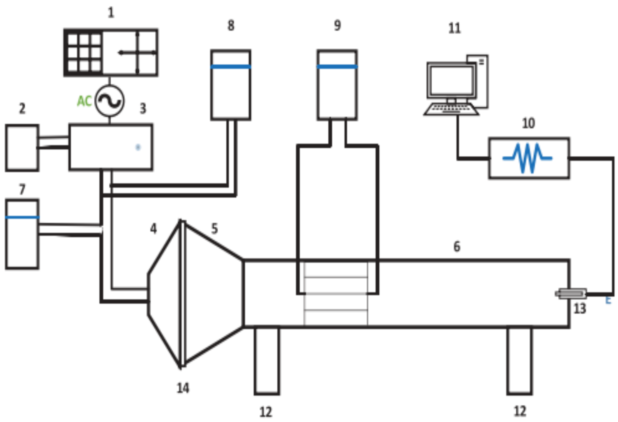

Figure 2.22: The schematic diagram for the experimental setup for the the stack geometric parameters effect on the resonator frequency. (Alamir, et. al, 2019)

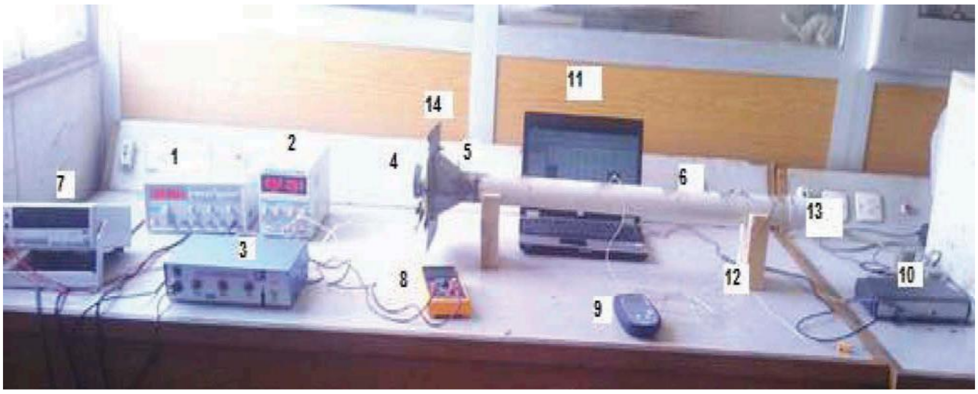

Figure 2.23: The experimental setup for the stack geometric parameters effect on the resonator frequency. (Alamir, et. al, 2019)

Based on Figure 2.22 and Figure 2.23, there are other apparatus that been in the experimental setup for the stack geometric parameters effect on the resonator frequency such as R.M.S measurement (number 7 and number 8), which has been used to check and control the watt of the power supply and microphone to see the resonance that happens in the resonator. By knowing this experimental setup, the future study in improving the thermoacoustic system can be done in the relationship of the resonance with the stacks inside the resonator. It may give a lot of understanding about the wave characteristic that happen inside the resonator.

According to Nsofor, et. al (2009), there is another experimental set up that can be used for the thermoacoustic system. Figure 2.24 shows the experimental setup for the thermoacoustic refrigeration system by using the sphere buffer. The purpose of using the sphere buffer is to produce the open-end condition into the Hofler's design resonator. Other than that, this experimental setup shows on how the positioning of the heat exchanger and the cold exchanger that been used in the experiment. With the presence of the cold exchanger, the thermoacoustic refrigeration system can be seen more effectively.

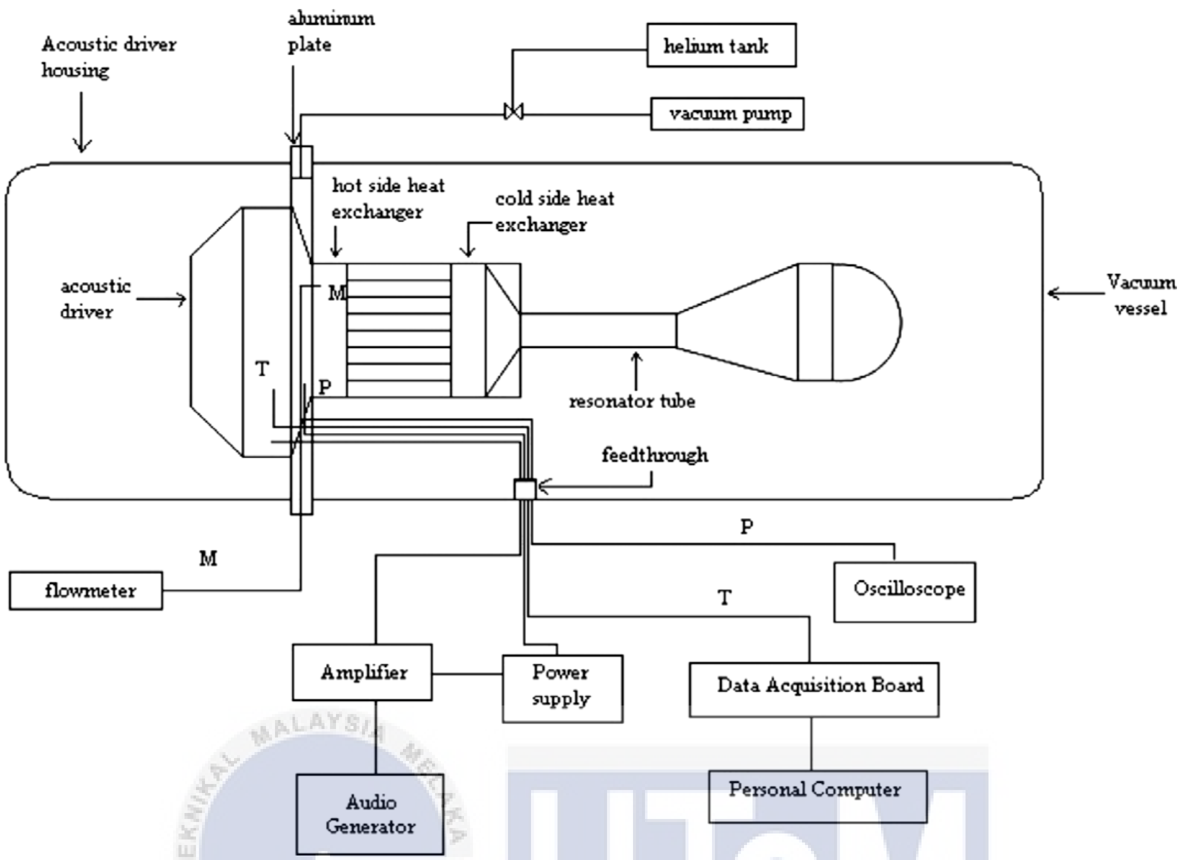

Figure 2.24: The experimental setup using the Hofler's resonator design.

2.8 Frequency and Wavelength used in the Thermoacoustic System.

There are two types of wavelengths that can be used in the thermoacoustic system. They are half-wavelength and quarter wavelength. Both wavelengths can be used in the thermoacoustic refrigeration system. According to Hariharan, et. al (2013), the application of the half-wavelength in the thermoacoustic system is suitable for the thermoacoustic heat engine and less suitable to be used for the thermoacoustic refrigeration system. While for the quarter wavelength, it is suitable to be used for the thermoacoustic refrigeration system according to Johari, et. al (2019).

Wave frequency is important to the thermoacoustic system. Increasing the efficiency of the thermoacoustic system, the wave frequency of the system must be fully utilized and use the right frequency. The frequency of the thermoacoustic system that been used in the test rig can be identified. The equation for finding the frequency has been provided by Lin, et. al (2021).

$$\lambda = c\ /f \tag{2.1}$$

Where, λ is the wavelength, c is wave speed, f is frequency. The known value for the c is 343m/s.

We can rearrange the equation in (2.1) to determine the frequency. Then after rearranging equation (2.1), it will become,

$$f\ =\ c/\lambda \tag{2.2}$$

According to Lin, et. al (2021), we must know the wavelength that we want to use. For example, if we decide to use half-wavelength so the λ will become ½ λ = ½ wavelength = the resonator length. If we decide to use quarter wavelength, so the λ will become ¼ λ = ¼ wavelength = the resonator length.

$$\frac{1}{4\lambda} = l \tag{2.3}$$

Where, *l* is the resonator length.

After we manage to find the λ, we insert the λ into equation (2.2) to get the frequency value.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology for the fabrication process and the experiment setup that been used in this project. The flow chart of the project is shown in Figure 3.1. This project begins with collecting the data and information about the standing wave in the thermoacoustic system. After all the data and information had been gathered, the literature review had been done about the standing wave in the thermoacoustic system. The purpose of doing the literature review is to get more understanding about the standing wave in the thermoacoustic system and the application of the system.

After done doing the literature review and designing for the mini test rig, as shown in Figure 3.2 for Mini Test Rig A and Figure 3.3 for Mini Test Rig B in the previous semester, the fabrication process had been done this semester. The experiment had been run to gather the result and making the discussion about the result that had been gathered. All the progress for this project in this semester and the previous semester had been shown in the Gantt chart in Appendix I and the Appendix II.

Figure 3.1 explained the flow chart of the methodology for the PSM I and PSM II that been done this semester for PSM II and in the previous semester for PSM I. In the previous semester, all the literature review and problem identification had been made for this research. A literature review process helps to understand the objective problem that needs to be solved in this research.

After the literature review and problem determination, the identification had been made, and the designing of both mini test rigs was done in the previous semester. The design for both mini test rigs has been done using the Solid Work software and based on the dimension that suitable for the fabrication process. The purpose of designing both mini test rigs with different diameter and length of the resonator is to see the relationship of the diameter and the length of the resonator with the velocity reading. These two parameters are the main elements that required to be explained in this research. Based on the literature review, only the length of the resonator has been highlighting as the component that helps in improving the efficiency of the thermoacoustic system. But the none of them are explaining about the relationship of the diameter of the resonator with the velocity reading of the wave inside the resonator.

The purpose of choosing the velocity as the responding variable for this research is because of the limitation of apparatus that can be used, and the velocity is the element that can be easy to be working with, safe and time limitation on using the laboratory due to the pandemic Covid-19. Based on the literature review, the other elements that need to be measure for improving the efficiency of the thermoacoustic refrigeration system are the pressure, the position of the stacks inside the resonator, the gap between the stacks inside the resonator, and the type of stacks that been used. These other elements cannot be covered in this research due to the time limitation in using the laboratory and the apparatus of measurement that has been used. But it can be done in future research.

For this semester, the fabrication for both mini test rigs had been done in week three of this semester. After done the fabrication process, additional reading about the wave distortion had been done to repair the literature review and to make some calculations for finding the best frequency that needs to use in the experiment for this research which meet the objective of this research. Next, the measurement of the standing wave in the thermoacoustic system with the variable parameter had been identified and been had been understood for this research. The parameter that has been a highlight for this research is to see the relationship between the diameter of the resonator and the velocity reading and to see the wave distortion that occurred in the system.

After understanding the parameter that been highlight in this research, the experiment for this research had been done, and the data of the experiment had shown in CHAPTER 4. To make sure the data is sufficient in understanding the wave characteristics and the distortion of the wave, some discussion on the data had been done with my supervisor. After that, the discussion about the results gathered had been presented in the report for this research.

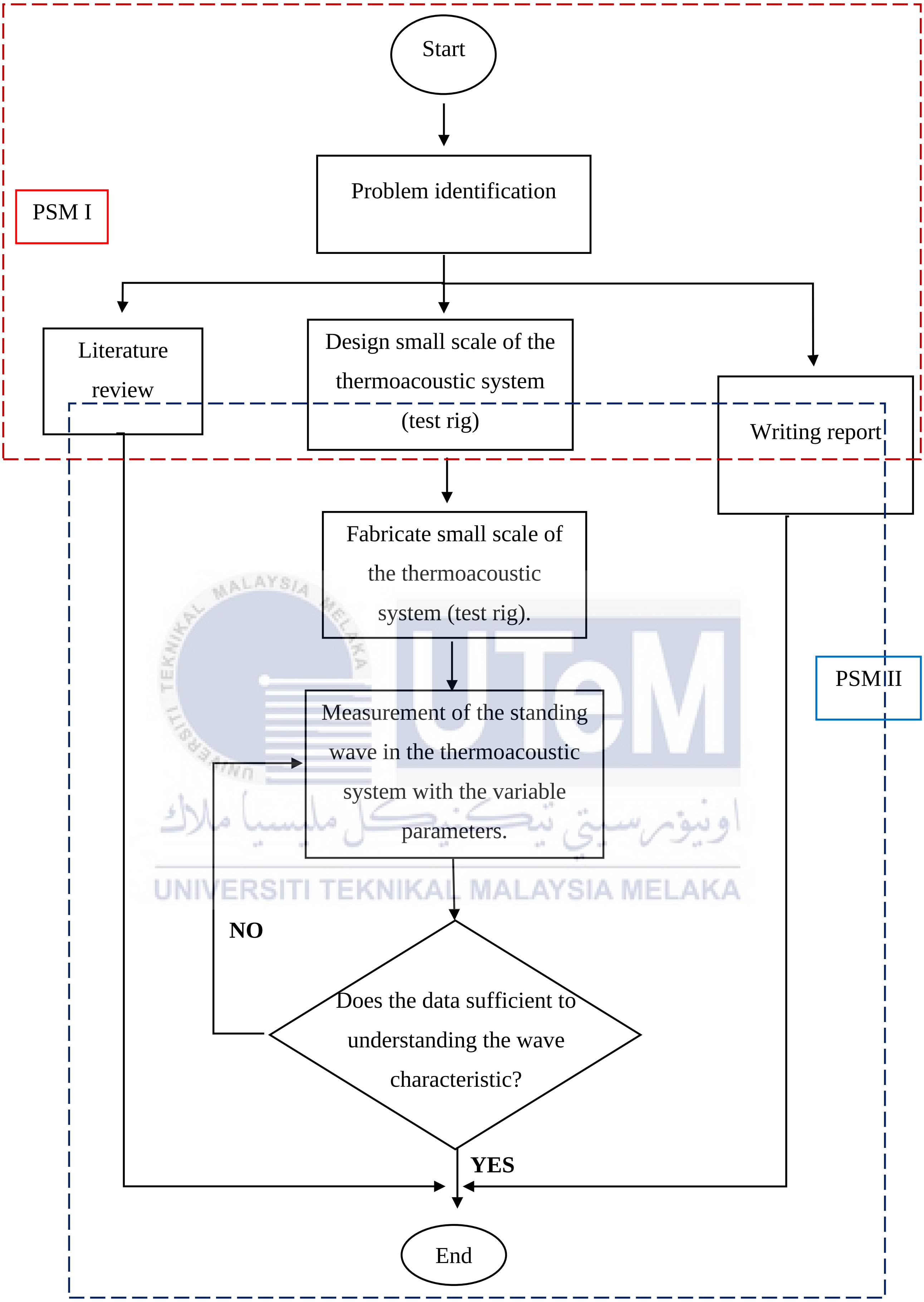

Figure 3. 1: The flow chart of the methodology for the PSM I and PSM II.

3.2 Fabrication Process for The Mini Test Rig.

This part explains the fabrication process of the mini test rig for the thermoacoustic system. The drawing diagram for the system is shown in Figure 3.2 for the Mini Test Rig A and Figure 3.3 for the Mini Test Rig B. The fabrication process for both mini test rigs consist of two parts which are the assembly part and the finishing part. Firstly, we must purchase all the materials required, such as the speaker, the plywood, the PVC pipe, glue, nails, and screws. Then, the steps for the fabrication process continue, as explained below.

Steps for the fabrication process of the mini test rig:

i. After purchasing the plywood, the plywood has been cut into six parts with dimensions 0.3m X 0.3m as shown in Figure 3.4. One of the plywoods that had been cut (front part) has been drilled at the center to make a hole to connect the PVC pipe (the resonator) with the storage. The cutting process of the plywood had been shown in Figure 3.2 for Mini Test Rig A and in Figure 3.3 for Mini Test Rig B

ii. The six parts of the plywood had been assembled to form the storage part using the nails and glue to make sure to strong and can hold the speaker.

iii. Next, the PVC pipe (the resonator) has been cut with the dimension 0.8m and drilled seven holes on the top surface of the PVC pipe with the distance between one hole with another hole is 0.1 m.

iv. After that, the PVC pipe (the resonator) has been assembled with the storage at the center of the storage using glue.

v. After done the assembly process of the storage part and the PVC pipe, the speaker has been placed inside the storage using the screw to make sure the speaker is not moving while running the experiments.

vi. The sponge has been used to fill in inside the store to avoid the noise from the speaker come out from the storage.

vii. After done all the fabrication processes, wood shellac has been used on the storage part as the finishing to make sure the storage is capable provide water resistance, as shown in Figure 3.5 below.

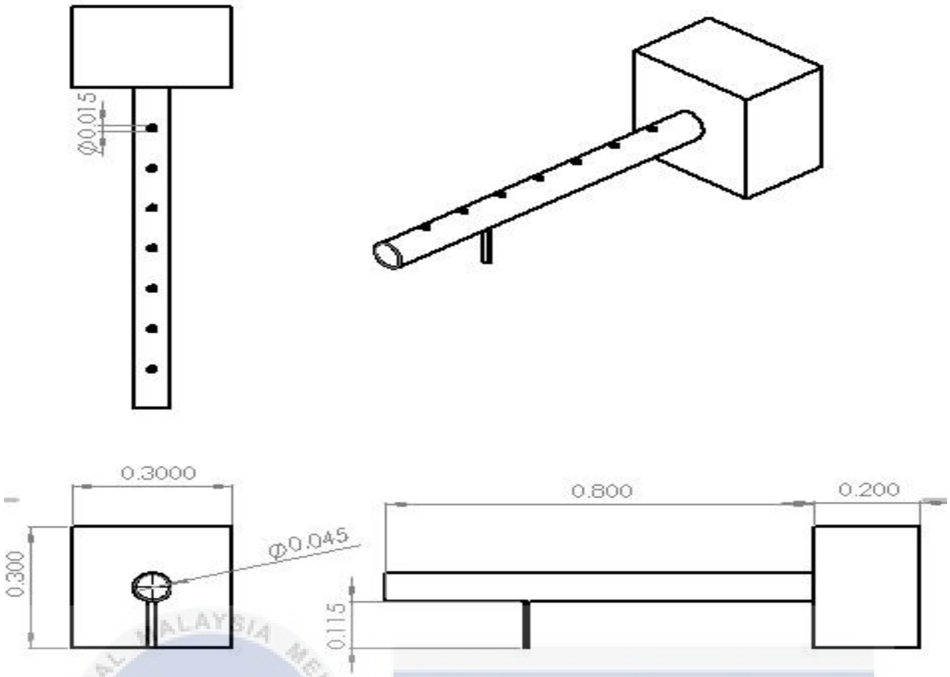

Figure 3.2: The drawing diagram for Mini Test Rig A.

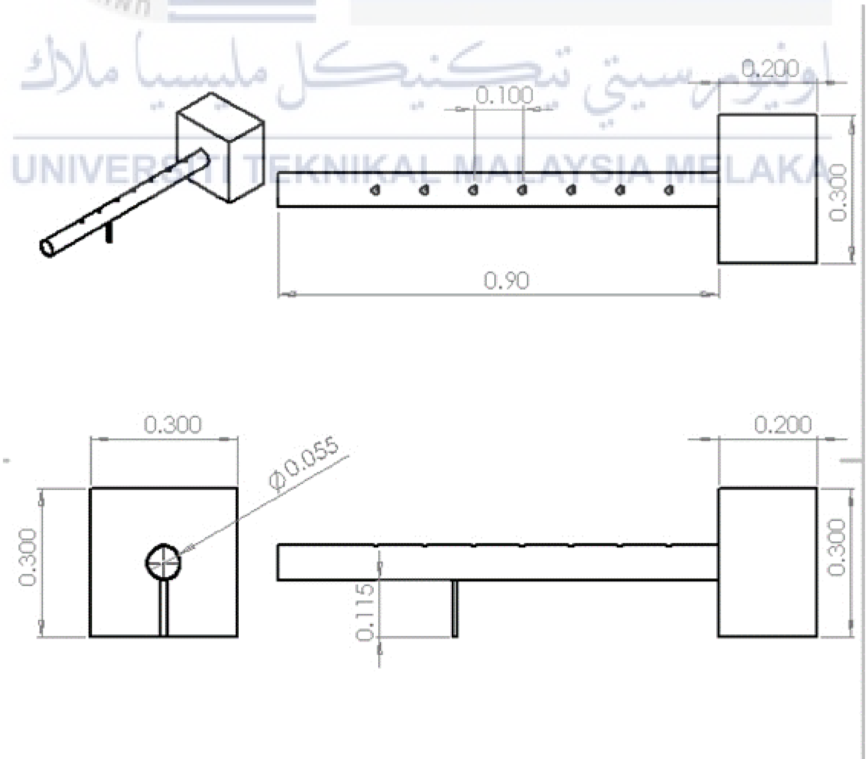

Figure 3.3: The drawing diagram for Mini Test Rig B.

Figure 3.4: The cutting process for the plywood.

Figure 3.5: The mini test rig for the thermoacoustic system.

3.3 The Experimental Set up for the Thermoacoustic System.

The experiment using the mini test rig had been done before. The objective of experiment activities is to determine whether the occurrence of wave distortion in the small-scale thermoacoustic system. The experiment also had been done using the actual test rig at the Turbomachinery lab. All the procedure of the experiment is same although using the mini test rig or the actual test rig for the thermoacoustic system. The procedure and set-up for the experiment are explained below.

Experimental procedure for mini test rig of the thermoacoustic system:

i. Connect the wire (positive and negative terminal) from the amplifier to the speaker inside the storage of the test rig.
ii. Cover all the holes on the resonator surface and at the end of the resonator using the plasticine clay.
iii. Switch on the power supply and insert the frequency that has already been calculated before (123 Hz) in the amplifier.
iv. After that, let the speaker generate the wave for 1 minute before taking the data. The purpose of doing this is to let the wave move freely inside the resonator.
v. After 1 minute, we can start taking the data using the velocimeter. Make sure to place the velocimeter perpendicular to the resonator. The sensor of the velocimeter is facing the speaker where the wave comes from and make sure the surrounding of the velocimeter is tightly cover with the plasticine clays on top of the hole to avoid the wave moving out from the resonator while running the experiment, as shown in Figure 3.6.
vi. After done taking data at the first hole, the step iv and v have been repeated for the next other holes.
vii. After done repeating steps iv and v for the seven holes, the experiment has been repeated three times to see the consistency of the results.
viii. All the data that has been gathered, has been stored using Table 4.1.

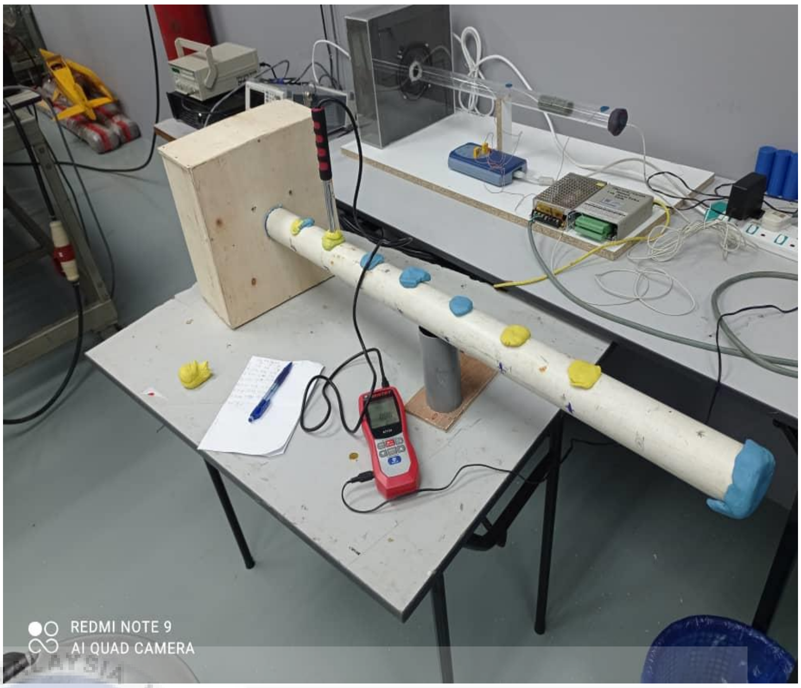

Figure 3.6: The experimental set-up for the test rig of the thermoacoustic system.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will explain the observation and the results obtained from the research. All the data that have been gathered were tabulated and illustrated in the figure. The results obtained were analysed, and the discussion was made based on the understanding in the literature review.

4.2 Actual Test Rig for The Thermoacoustic System

The actual test rig for the thermoacoustic system was also tested to compare results with the mini test rigs that was fabricated. The actual test rig has been placed in the Turbomachinery Lab, and the data that have been gathered are shown in Table 4.1(a). The components of the actual test rig consist of the speaker, resonator, and the stack. The speaker that has been used in the actual test rig is bigger than the mini test rig. The actual test rig has seven meters for the resonator, used quarter wavelength, and used 14.2 Hz for its frequency. The procedure of running the experiment is the same as the procedure that has been used for both mini test rigs.

Table 4.1(a): Result for the thermoacoustic test rig.

Point	Distance from a speaker(m)	Velocity reading (m/s)			
		1st	2nd	3rd	Average
1	1.84	5.17	5.16	5.17	5.17
2	2.39	5.39	5.37	5.47	5.39
3	3.76	4.92	4.91	4.92	4.92
4	4.25	4.66	4.57	4.75	4.66

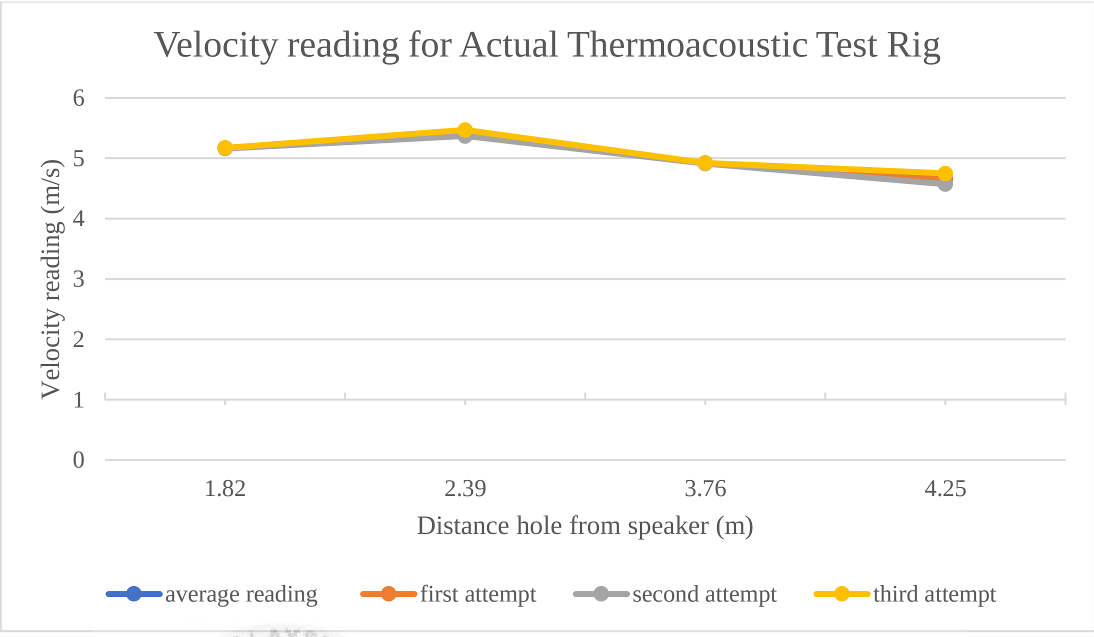

Figure 4.1(b): Velocity reading for actual thermoacoustic test rig.

Figure 4.1 (b) shows the velocity reading against the distance travel by the wave inside the resonator for the actual thermoacoustic test rig. We can see the pattern of the result, and it undergoes an increasing pattern from the first point until the second point, which is at 2.39 m from the speaker. After 2.39 m, we can see that the velocity reading is showing decreasing pattern until the last points, which is 4.25 m away from the speaker. The pattern of the wave remains unchanged even it has been tested three times. The purpose of doing testing three times using the velocimeter is to see whether the wave properties inside the resonator is changing or not and to avoid the mishandling of the velocimeter. The average reading has been taken from the three readings to help easy to make the discussion about the results.

From this result, we can say that the actual thermoacoustic test rig may be undergoing the distortion wave. The reason for saying these due to the results that show after the second point, which is showing a decreasing pattern. The decreasing pattern show in the other two attempts with a small different reading. We understand that the acoustic wave that has been used in the thermoacoustic system capable of propagating itself inside the resonator, and the results of the velocity reading for this test rig should show an increasing pattern at the final point after having some decreasing pattern. The wave may undergo distortion, and the wave may be lost to the surrounding.

4.3 Mini Test Rig

A mini test rig has been used to identify and gather information about the wave properties on a smaller scale. Other than that, the mini test rig also has been used in this research is to see whether wave distortion may occur in the thermoacoustic system or not and to gather the data for choosing the best design with high efficiency of the thermoacoustic system.

For this research, two mini test rigs shown in Figure 4.2 are the Mini Test Rig A, and Figure 4.3 is the Mini Test Rig B. For the Mini Test Rig A, the dimension is the same as the previous design, which is used 0.8 m length of the pipe PVC as the resonator, and the hole interval is 0.1 m. For the Mini Test Rig B is has been shown in Figure 4.3, the shape of the storage of the speaker is equal to the Mini Test Rig A, but the difference between Mini Test Rig A with the Mini Test Rig B is the diameter of the resonator, which is the diameter of the PVC pipe and the length of the pipe. For the Mini Test Rig A, the diameter of the pipe is 0.045m and 0.8m in length, while the diameter for the Mini Test Rig B is 0.055m with 0.9m in length. Both mini test rigs used quarter wavelength in this research.

Figure 4.2: Mini Test Rig A

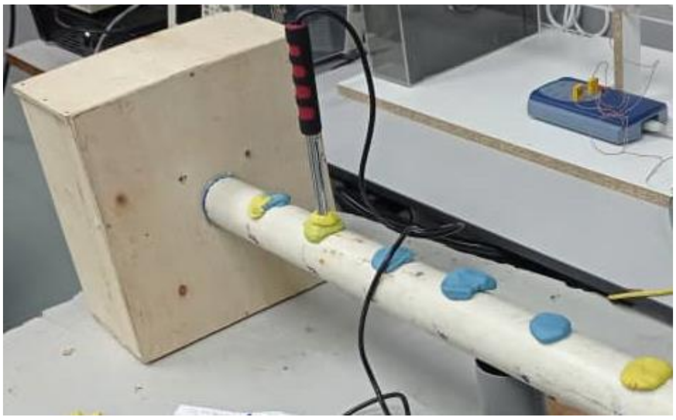

Figure 4.3: Mini Test Rig B

4.4 Determination for The Frequency Used in The Mini Test Rig.

Frequency is important in a thermoacoustic system because the frequency is the main component in improving the efficiency of the thermoacoustic system. Below is the calculation to find the frequency for both mini test rigs.

The equation of

$$\lambda = c / f \tag{2.1}$$

Where λ is the wavelength, c is wave speed, and f is frequency. The known value for the c is 343m/s.

We can rearrange equation in (2.1) to determine the frequency. Then after rearranging equation (2.1), it will become,

$$f = c/\lambda \tag{2.2}$$

Wavelength is equal to the length of the resonator. The quarter-wavelength has been used in this research for both mini test rigs. For the Mini Test Rig A, the ¼ wavelength is equal to the 0.8 m and the frequency is 107.19 Hz. For the Mini Test Rig B, ¼ wavelength is equal to 0.9 m and the frequency is 95.28 Hz. The maximum length of the holes from the speaker is 0.7m which the frequency is 122.5 Hz.

The calculation for the Mini Test Rig A:

¼ λ = ¼ wavelength = the resonator length.

$$\frac{1}{4\lambda} = l \tag{2.3}$$

Where, l is the resonator length and ¼ wavelength = 0.8m.

We use equation (2.3) to find the λ.

$$\frac{1}{4\lambda} = 0.8m$$

$$\lambda = (4X0.8m)$$

$$\lambda = 3.2m$$

After λ is found, we use equation (2.2) to find the frequency.

$$f = c/\lambda \tag{2.2}$$

$$f = 343\ (\frac{m}{s})/3.2m$$

$$f = 107.19\ Hz$$

Calculation for the Mini Test Rig B:

$$\frac{1}{4\lambda} = l \tag{2.3}$$

Where, l is the resonator length, ¼ λ = ¼ wavelength = the resonator length and ¼ wavelength is equal to 0.9m.

We use equation (2.3) to find the λ.

$$\frac{1}{4\lambda} = 0.9m$$

$$\lambda = (4X0.9m)$$

$$\lambda = 3.6m$$

After λ is found, we use equation (2.2) to find the frequency.

$$f = c/\lambda \tag{2.2}$$

$$f = 343\ (\frac{m}{s})/3.6m$$

$$f = 95.28\ Hz$$

Calculation for the maximum hole distance from the speaker.

$$\frac{1}{4\lambda} = l \tag{2.3}$$

Where, l is the resonator length, ¼ λ = ¼ wavelength = the resonator length and ¼ wavelength = 0.7m.

We use equation (2.3) to find the λ.

$$\frac{1}{4\lambda} = 0.7m$$

$$\lambda = (4X0.7m)$$

$$\lambda = 2.8m$$

After λ is found, we use equation (2.2) to find the frequency.

$$f = c/\lambda \tag{2.2}$$

$$f = 343\ (\frac{m}{s})/2.8m$$

$$f = 122.5\ Hz$$

The frequency 122.5 Hz has been rounding off to be 123 Hz that been during the experiment. The frequency 123 Hz has been selected in this research due to see the relationship of the main parameters of this research. The main parameters in this research are to see the relationship of the diameter and the length of the resonator in the system with the velocity reading. When we use the same frequency the velocity reading should be able to show small difference in the velocity reading because the frequency are the elements that generate the wave inside the resonator.

4.5 Result for The Mini Test Rig A

The experiment for the Mini Test Rig A has been done and using 123 Hz for the frequency. During running the experiment, the minimum amplitude and the maximum amplitude have been used to see the best result from these two amplitudes. The results in Figure 4.5(c) show that the maximum amplitude has the best reading compared to the minimum amplitude reading.

Amplitude: minimum

Frequency: 123 H

Table 4.4(a): Result for the Mini Test Rig A using minimum amplitude.

Point	Distance of hole from a speaker (m)	Velocity reading (m/s)			
		1st	2nd	3rd	Average
1	0.1	0.08	0.08	0.08	0.08
2	0.2	0.08	0.08	0.08	0.08
3	0.3	0.03	0.03	0.03	0.03
4	0.4	0.00	0.00	0.00	0.00
5	0.5	0.00	0.00	0.00	0.00
6	0.6	0.00	0.00	0.00	0.00
7	0.7	0.00	0.00	0.00	0.00

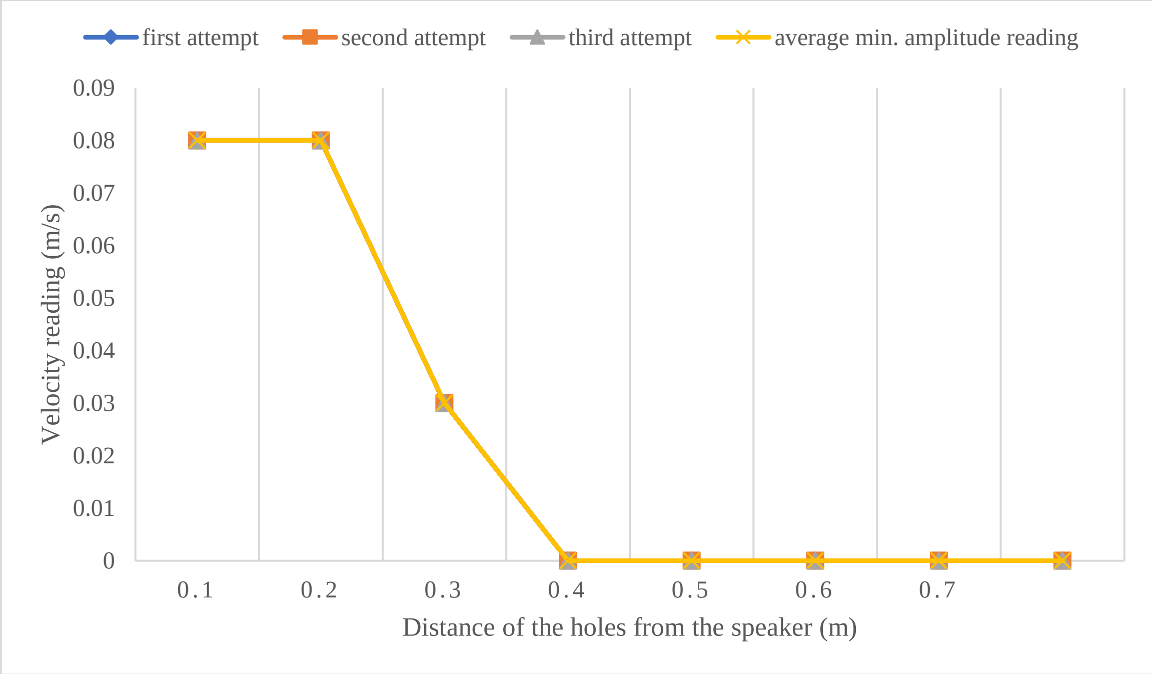

Figure 4.4(b): Velocity reading for Mini Test Rig A using minimum amplitude.

Figure 4.4(b) shows the velocity reading for the minimum amplitude against the distance travel by the wave inside the resonator for the Mini Test Rig A using the 123 Hz frequency. From the results, we can see the minimum amplitude shows constant reading from the first point to the second, which is 0.08 m/s. But after the second point's reading, its shows zero velocity reading starting from the fourth point until the seventh point. There is a huge different reading from the second reading with the fourth reading. This graph pattern remains unchanged for the next two attempts with the same velocity reading.

From the three-graph pattern that been shown in Figure 4.4 (b), we can see that the acoustic wave that been produced by the 123 Hz frequency with the minimum amplitude is only capable of travelling until the fourth point which 0.4 m from a speaker and after the second point it may be lost it energy until the fourth point, fully lost its energy and cannot be able to generate energy to travel after the fourth point until the seventh point which is 0.7 meter from a speaker. We can say that the minimum amplitude for the 123 Hz frequency is not suitable to be used in this experiment because the acoustic wave cannot be able to travel until the seventh point, and we also can say that the wave distortion may occur inside the resonator for this mini test rig due the decreasing pattern that occurred starting from the second point until the fifth point. But the zero-velocity reading for the fifth point until the seventh point makes it clearly lost its energy and does not be able to travel until the seventh point.

Amplitude: maximum

Frequency:123 Hz

Table 4.5(a): Result for the Mini Test Rig A using maximum amplitude.

Point	Distance of hole from a speaker (m)	Velocity reading (m/s)			
		1st	2nd	3rd	Average
1	0.1	0.99	1.08	0.99	1.02
2	0.2	1.06	1.09	1.06	1.07
3	0.3	1.06	1.09	1.06	1.07
4	0.4	0.97	0.91	0.97	0.95
5	0.5	0.77	0.61	0.70	0.69
6	0.6	0.80	0.75	0.75	0.77
7	0.7	0.82	0.81	0.81	0.81

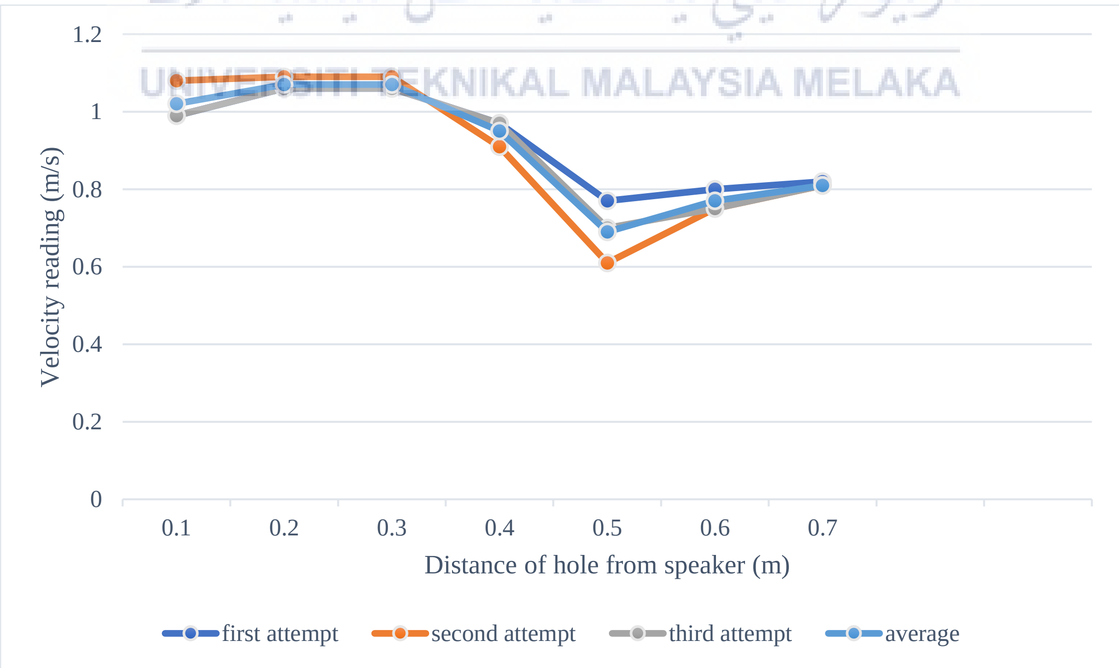

Figure 4.5(b): Velocity reading for the Mini Test Rig A using maximum amplitude.

Figure 4.5(b) shows the result of the velocity reading for the maximum amplitude for the 123 Hz against the distance travel by the acoustic wave inside the resonator for the Mini Test Rig A. The data have been taken for three-time to see the pattern of the acoustic wave travel inside the resonator and to the properties of the acoustic wave inside it. As we can see, the pattern of these three graphs remains constant but with different values. The graphs show an increasing pattern starting from the first point until the third point. The third attempt shows the lowest value for the first velocity reading compared to the other two patterns. This phenomenon occurred because the acoustic wave started to lose its energy at the first point during the reading taken for the third attempt.

After that, the graphs show decreasing pattern starting from the third point until the fifth point inside the resonator. These decreasing patterns happen in three attempts of reading taken because the acoustic wave shows that its starts to lose its energy. We can say that the wave distortion may occur in this area between 0.3 m to 0.5 m from a speaker. Even though it shows decreasing pattern from the third point until the fifth point, the graphs show an increasing pattern after the fifth point until the seventh point.

This phenomenon occurs due to the propagation of the acoustic wave inside the resonator. Even the acoustic wave capable to propagate inside the resonator, but the values of the velocity reading that been taken for the third point until fifth point which this area we suspect that wave distortion occurred shows decreasing values and we can say that the wave distortion may occurred rapidly in this design for the next five attempts.

We can conclude that the 123 Hz with maximum amplitude capable of generating the acoustic wave that managed to travel until to the seventh points, which 0.7 m from a speaker, and the wave distortion may occur in this design starting from the third point until the fifth but the acoustic wave inside the resonator capable propagating and of regenerating the acoustic wave until the seventh point which is 0.7 m from a speaker. Some maintenance needs to be done for this design to reduce the wave distortion that we suspected may occur at the third point until the fifth point by placing the insulator at these areas.

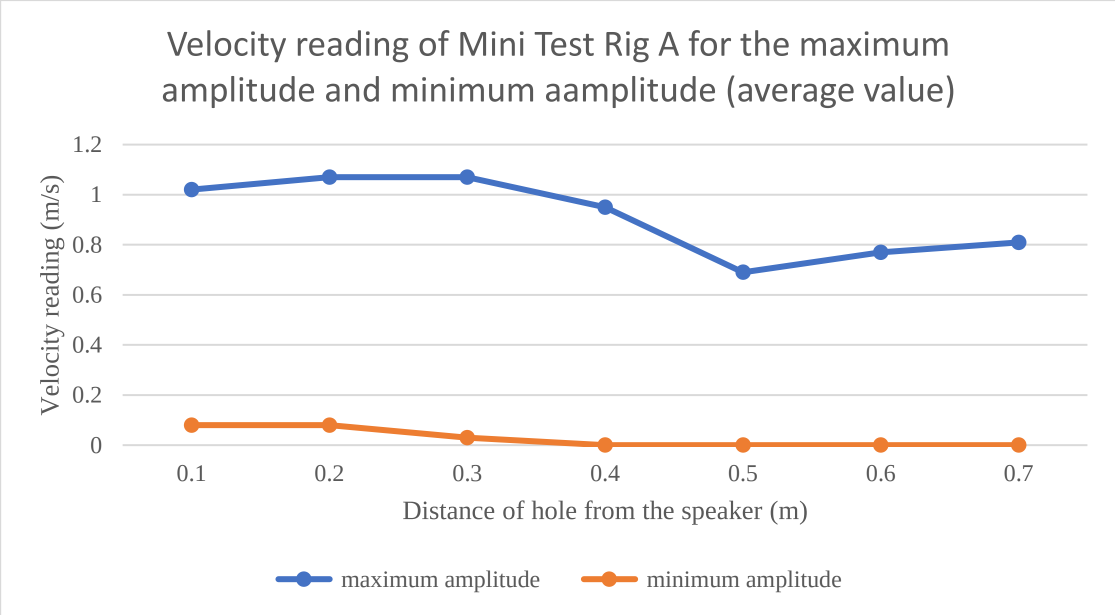

Figure 4.5(c): Velocity reading of the Mini Test Rig A for the maximum amplitude and minimum amplitude (average value)

Figure 4.5(c) shows the average velocity reading for both minimum amplitude and maximum amplitude for the 123 Hz frequency that has been used in the Mini Test Rig A against the distance travel by the acoustic wave in the resonator. We can see a huge difference between both amplitudes in velocity reading. The maximum amplitude has higher reading compared to the minimum amplitude and the graph pattern is also showing the difference in pattern. Even they use the same frequency, the pattern for the average reading of the minimum amplitude is decreasing starting from the second point until the fourth point and show zero velocity reading from the fourth point until the seventh point.

For the average reading of the maximum amplitude, the graph pattern showed decreasing starting from the third point until the fifth point only and managed to show the increasing pattern until the seventh point. We can say that the minimum amplitude only manages to generate acoustic waves until the fourth point, but the acoustic wave cannot be able to regenerate or propagate itself and travel until the seventh point. We also can say that the wave distortion may occur in this amplitude due to the decreasing pattern that has been shown, but the zero-velocity reading between the fourth point until the seventh points shows that the minimum amplitude cannot be able to generate acoustic wave to travel until to the seventh point.

From the result that has been shown in Figure 4.5(c) we can understand that the amplitude also has an impact on improving the efficiency of the thermoacoustic refrigeration system. Even using the same amount of frequency but the amplitude used is different, it may affect the results and the efficiency of the thermoacoustic system. For the Mini Test Rig A, the maximum amplitude is the best to be used and can be able to give better results during the experiment.

4.6 The Result for the Mini Test Rig B.

Minimum amplitude

Frequency: 123 Hz

Table 4.6(a): Result for the Mini Test Rig B using minimum amplitude.

Point	Distance of hole from a speaker (m)	Velocity reading (m/s)			
		1st	2nd	3rd	Average
1	0.1	0.09	0.09	0.09	0.09
2	0.2	0.09	0.09	0.09	0.09
3	0.3	0.05	0.05	0.05	0.05
4	0.4	0.02	0.02	0.02	0.02
5	0.5	0.00	0.00	0.00	0.00
6	0.6	0.00	0.00	0.00	0.00
7	0.7	0.00	0.00	0.00	0.00

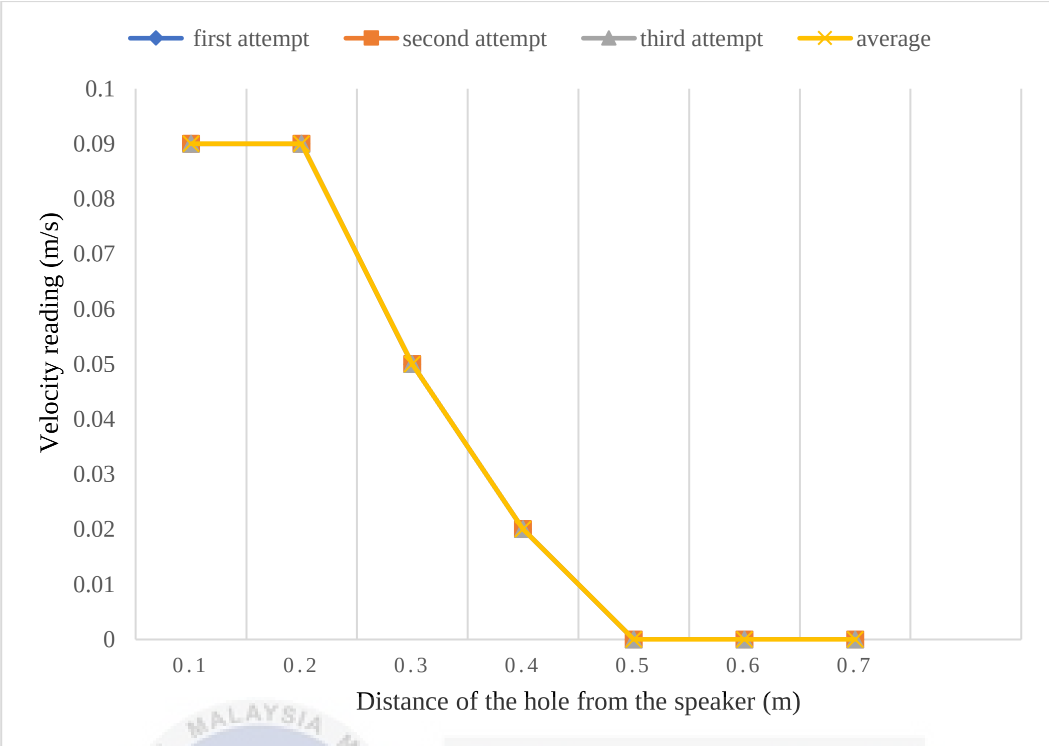

Figure 4.6(b): Velocity reading for the Mini Test Rig B using minimum amplitude.

Figure 4.6(b) shows the velocity reading for the minimum amplitude against the distance travel by the wave inside the resonator for the Mini Test Rig B using the 123 Hz frequency. From the results, we can see the minimum amplitude shows constant reading from the first point to the second point, which is 0.09 m/s. But after the second point's reading, it shows decreasing pattern until the fifth point and shows zero velocity reading starting from the fifth point until the seventh point. There is a huge different reading from the second reading with the fifth reading. This graph pattern remains unchanged for the next two attempts with the same velocity reading.

From the three-graph pattern that been shown in Figure 4.6 (b), we can see that the acoustic wave that been produced by the 123 Hz frequency with the minimum amplitude is only capable of traveling until the fifth point, which 0.5 m from a speaker and after the second point it starts to lose it energy and cannot be able to generate energy to travel until the seventh point which is 0.7 m from a speaker. We can say that because the velocity reading for the fifth point is zero until the seventh point. We can say that the minimum amplitude for the 123 Hz frequency is not suitable to be used in this experiment because the acoustic wave cannot be able to travel until the seventh point and we also can say that the wave distortion may occur inside the resonator for this mini test rig due the decreasing pattern that occurred starting from the second point until the fifth point. But the zero-velocity reading for the fifth point until the seventh point makes it clearly lost its energy and did not be able to travel until the seventh point.

Maximum amplitude

Frequency: 123 Hz

Table 4.7(a): Result for the Mini Test Rig B using maximum amplitude.

Point	Distance of hole from a speaker (m)	Velocity reading (m/s)			
		1st	2nd	3rd	Average
1	0.1	0.68	0.68	0.56	0.64
2	0.2	0.70	0.69	0.56	0.65
3	0.3	0.67	0.65	0.56	0.63
4	0.4	0.60	0.59	0.54	0.58
5	0.5	0.51	0.47	0.46	0.48
6	0.6	0.39	0.35	0.39	0.38
7	0.7	0.34	0.34	0.34	0.34

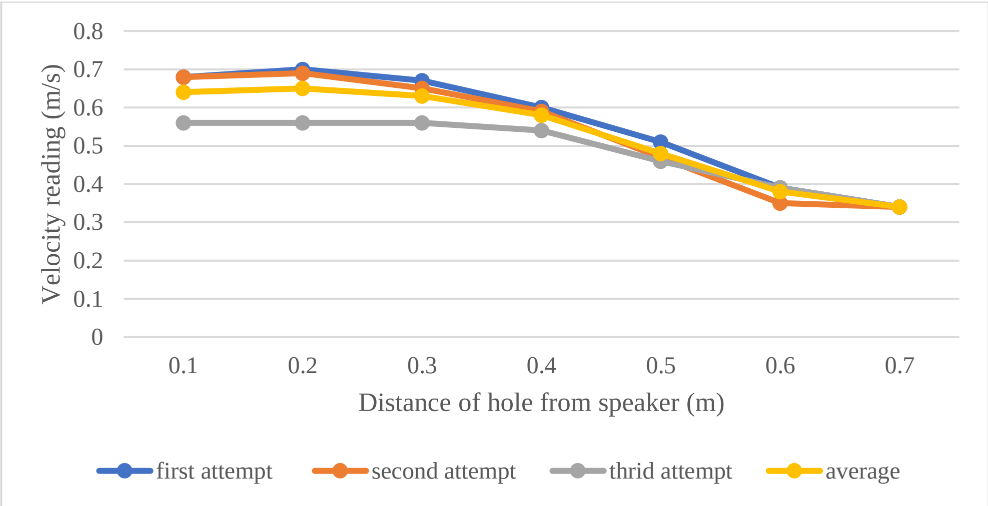

Figure 4.7(b): Velocity reading for the Mini Test Rig B using maximum amplitude.

Figure 4.7(b) shows the result of the velocity reading for the maximum amplitude for the 123 Hz against the distance travel by the acoustic wave inside the resonator for the Mini Test Rig B. The data have been taken three times to see the pattern of the acoustic wave travel inside the resonator and to the properties of the acoustic wave inside it. As we can see, the pattern of these three graphs remains constant but with different values. The graphs show an increasing pattern starting from the first point until the second point for the first and second attempts. But for the third attempt shows the constant value for the velocity reading starting from the first point until the third point which is 0.56 m/s. This phenomenon occurred because the acoustic wave started to lose its energy to the surrounding during the reading taken for the third attempt.

After that, the graphs show decreasing pattern staring from the fourth point until the seventh point inside the resonator. These decreasing patterns happen in three attempts reading taken because the acoustic wave shows that it starts to lose its energy. We can say that the wave distortion may occur in this area between 0.4 m to 0.7 m from a speaker. Even the wave distortion occurred in this test rig's design, but the acoustic wave that been generated by the 123Hz manage to travel along the resonator length. In these results, we can see that the acoustic wave inside the resonator cannot be able to propagate itself and show an increasing pattern which we can see in Figure 4.5(b) for the Mini Test Rig A after having a decreasing pattern.

We can conclude that the 123 Hz frequency with maximum amplitude capable of generating the acoustic wave that manged to travel until to the seventh points, which 0.7 m from a speaker and the wave distortion may occur in this design starting from the fourth point until the seventh point is 0.7 meter from a speaker. Some maintenance needs to do for this design to reduce the wave distortion that we suspected may occur from the fourth point until the last point by placing the insulator at these areas and using the smaller diameter of the resonator.

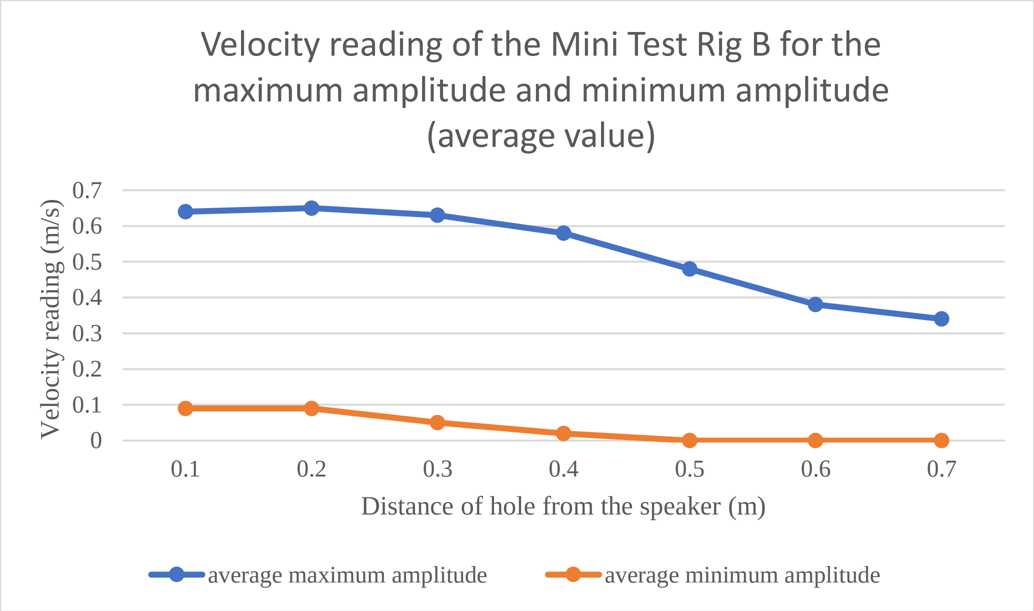

Figure 4.7(c): Velocity reading of the Mini Test Rig B for maximum amplitude and minimum amplitude (average value).

Figure 4.7(c) shows the average velocity reading for both minimum amplitude and maximum amplitude for the 123 Hz frequency that has been used in the Mini Test Rig B against the distance travel by the acoustic wave in the resonator. We can see a huge difference between both amplitudes in velocity reading. The maximum amplitude has a higher reading than the minimum amplitude, and the graph pattern also shows the difference in pattern. Even they use the same frequency, the pattern for the average reading of the minimum amplitude is decreasing starting from the second point until the fifth point and shows zero velocity reading starting from the fifth point until the seventh point.

For the average reading of the maximum amplitude, the graph pattern also decreases from the second points until the seventh point. We can say that the minimum amplitude only manages to generate acoustic waves until the fourth point, but the acoustic wave cannot be able to regenerate or propagate itself and travel until the seventh point. We also can say that the wave distortion may occur in this amplitude due to the decreasing pattern that has been shown, but the zero-velocity reading between the fifth point until the seventh points shows that the minimum amplitude does not have the energy to generate acoustic wave to travel until to the seventh point.

From the result shown in Figure 4.7(c), we can understand that the amplitude also impacts the efficiency of the thermoacoustic refrigeration system. Even using the same amount of frequency but the amplitude used is different may affect the results and the efficiency of the thermoacoustic system. For the Mini Test Rig B, the maximum amplitude is the best to be used and can be able to give better results during the experiment.

4.7 Comparison Between the Mini Test Rig A with the Mini Test Rig B

This sub chapter explains the result in both the mini test rig and the discussion that can be made from the results. The discussion for the results consists of the average maximum amplitude reading and the graph pattern to identify whether wave distortion occurred in both mini test rigs.

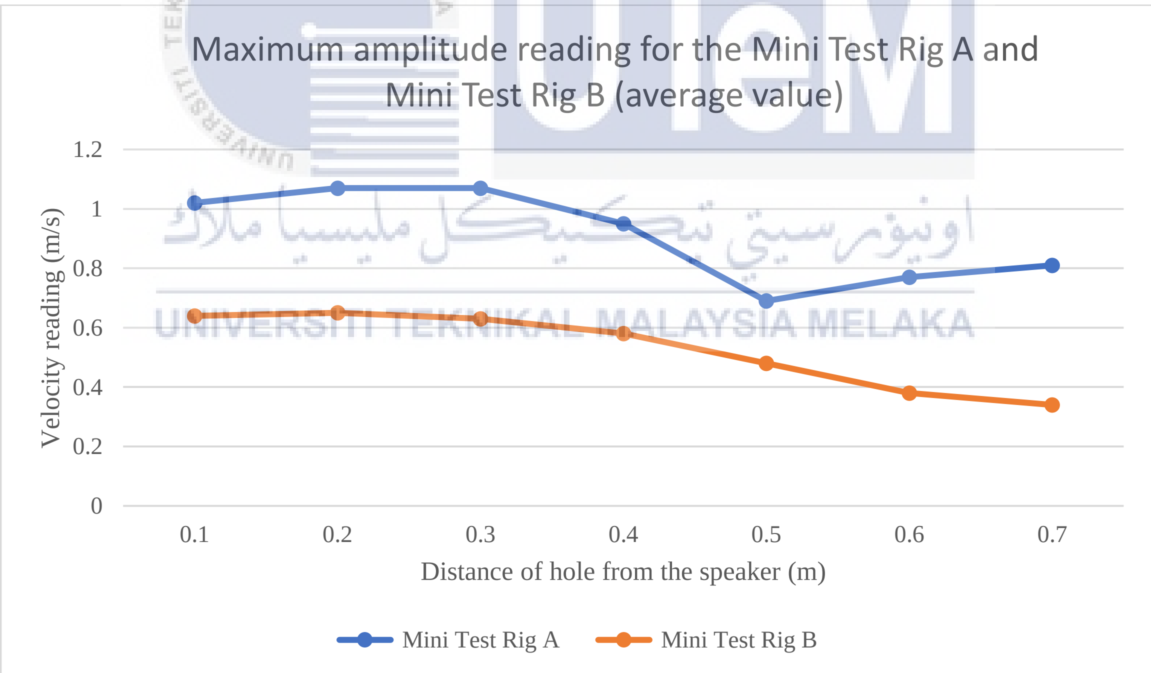

Figure 4.8: Maximum amplitude reading for the Mini Test Rig A and the Mini Test Rig B (average value)

Figure 4.8 shows the comparison between the average velocity reading for the Mini Test Rig A and the Mini Test Rig B for the 123 Hz frequency against the distance travel by the acoustic wave in the resonator. We can see a huge different velocity reading between both mini test rig velocity reading. The Mini Test Rig A has higher reading than the Mini Test Rig B, and the graph pattern also shows the difference in pattern. Even they are using the same frequency, the pattern for the average reading of the Mini Test Rig A is increasing starting from the first point until the third point, while for the Mini Test Rig B only manage to show a small increasing pattern starting from the first point until the second point. Both mini test rigs show the decreasing pattern which we can say that this decreasing pattern is the area where the wave distortion occurred.

For the Mini Test Rig A, the graph pattern shows decreasing starting from the third point until the fifth point, and after that, the acoustic wave manages to regenerate and propagate itself by showing the increasing pattern starting for the rest of the point. The distance of the seventh point with the end of the resonator also helps the acoustic wave inside the Mini Test Rig A to propagate itself. The distance of the seventh point with the end of the resonator is 0.1 m. For the Mini Test Rig B, the graph pattern decreases from the second point until the seventh point. The acoustic wave for this mini-test rig does not regenerate and propagate itself due to the wave distortion accorded inside the resonator and because of the distance between the seventh point and the end of the resonator. The distance between the seventh point with the end of the resonator for the Mini Test Rig B is 0.2 m which much bigger compared to the distance for the seventh point with the end of the resonator for the Mini Test Rig A.

From the results, we can say that the Mini Test Rig B undergoes higher wave distortion compared to the Mini Test Rig A. The Mini Test Rig A used 0.045 m for the resonator diameter and 0.8 m for the length of the resonator. Meanwhile, the Mini Test Rig B used 0.055 m for the diameter of the resonator and 0.9 m for the resonator's length, which is much bigger than the Mini Test Rig A

From the comparison above, we can see that the difference in the diameter, the length of the resonator, and the distance of the seventh point with the end of the resonator may affect the velocity reading for the test rig and may increase the chance of wave distortion in the test rig. The bigger the diameter, the longer the length of the resonator, and the shorter the distance of the seventh point with the end of the resonator, the higher the chance of wave distortion may occur in the system. When the diameter of the resonator is bigger, the length of the resonator is longer, and the distance required for the acoustic wave to travel also becomes longer and increases the chance of wave distortion occurring. When the shorter the distance between the seventh point with the end of the resonator, the acoustic wave be able to regenerate itself and reduce the chance for the wave distortion to occur.

Figure 4.8 shows that even the frequency is the same which 123 Hz that been used in this research, and the final distance of the seventh hole is the same which is 0.7m. The result may be different due to the diameter and the length of the resonator. Figure 4.8 also shows the difference in distance between the seventh point with the end of the resonator may affect the chance of the wave distortion to occur. So, we can conclude that the diameter, the length of the resonator, and the distance between the seventh point with the end of the resonator are significant parameters that can help in improving the efficiency of the thermoacoustic refrigeration system.

The reason for using the frequency 123 Hz for both mini test rigs' designs is to check the suitability of the frequency 123 Hz for both designs and for seeing the relationship of the main parameters for this research. The wave distortion may undergo in both designs of the mini test rig due to the diameter, the length of the resonator used, and the suitability of the frequency used.

Repeatability while running the experiment is important. This is because we can get a better result and manage to see the reproductivity of the wave.

CHAPTER 5

CONLUSION AND RECOMMENDATION

5.1 Conclusion

Based on the results, we can conclude that the wave distortion in the thermoacoustic refrigeration system is difficult to be identified using only the velocity, which is it required other elements such as the pressure and the temperature difference. We only can assume based on the decreasing pattern that has been shown in the velocity reading. If there is another responding variable, such as the pressure reading and temperature difference inside the resonator, we can approve and see more about the wave distortion that is occurred in the system. But in this research, we managed to gather important information, which is the diameter of the resonator and the distance between the seventh point with the end of the resonator also have contributed to improving the efficiency of the thermoacoustic refrigeration system. Other than that, the length of the resonator and the amplitude selection for the frequency of the system also give effect to the efficiency of the thermoacoustic refrigeration system, and chances of wave distortion may occur in the system.

Using the right diameter of the resonator will help to reduce the chances of wave distortion that may occur in the system and increasing the efficiency of the thermoacoustic refrigeration system. The smaller the diameter of the resonator, the further the wave can travel in the resonator using the energy that has been generated by the speaker. Small diameters help better oscillation and propagation of the acoustic wave inside the resonator. When the acoustic wave inside the resonator can be fully utilized, a better thermoacoustic refrigeration system can be produced. These can be seen during the research; the Mini Test Rig A manages to regenerate an increasing pattern at the fifth point after it has a decreasing pattern. While the Mini Test Rig B cannot regenerate the increasing pattern after the fifth, it continues decreasing until the last points.

Using the right distance of the seventh point with the end of the resonator help to reduce the wave distortion that may occur in the system. The shorter the distance between the seventh point with the end of the resonator, the acoustic wave inside the resonator be able to propagate itself. This can be seen in the result that the Mini Test Rig A with 0.1 m distance between the seventh point and the end of the resonator is capable to propagate itself by showing an increasing pattern at the sixth and seventh point while for the Mini Test Rig B the distance of the seventh point with the end of the resonator is 0.2 m which bigger than Mini Test Rig A unable to show any propagation of acoustic wave inside the resonator.

Using the right amplitude also can give better results for the thermoacoustic refrigeration system. This can be seen in both mini test rigs and the minimum amplitude shows do not be able to travel until the seventh point and shows some characteristic of the wave distortion occurred due to the decreasing pattern that ben shows in the result. But due to the zero-velocity reading for both mini test rigs for the minimum amplitude, we cannot assume that the minimum amplitude undergoes wave distortion but the incapability of the acoustic wave that has been produced with the minimum amplitude inside the resonator to travel until to the seventh point.

We can say that using the maximum amplitude and with the right diameter of the resonator can help to improve the efficiency of the thermoacoustic refrigeration system. The reason for saying this is due to the results that had been shown for both mini test rigs. Even the using the maximum amplitude, but without using the right diameter for the resonator, the efficiency of the thermoacoustic refrigeration system still cannot be maximized. As we can see in the result for the Mini Test Rig A, using the maximum amplitude and the right diameter of the resonator, the wave distortion characteristic occurred in the system only in between the third point until the fifth point. Compare to the Mini Test Rig B which also uses maximum amplitude, but the diameter of the resonator is bigger than the Mini Test Rig A, the wave distortion characteristic occurred in the system starting from the second point until the last point. We can say that using the maximum amplitude with the right diameter of the resonator, the wave distortion characteristic that may occur in the system can be minimized due to the capability of the acoustic wave to propagate and regenerate itself.

For this research, we can conclude that the design for the Mini Test Rig A is better than the design for the Mini Test Rig B in terms of the wave distortion that may occur. We can assume both undergo the wave distortion but due to the leak of information from another responding variable such as the pressure and the temperature difference, the only assumption can be made. Maybe for the next future work can approve this assumption is right with the other evidence instead of only using the velocity reading of the acoustic wave.

There is still a lot of works to do in understanding the wave distortion characteristic and to increase the efficiency of the thermoacoustic refrigeration system. From my understanding, when the wave distortion can be minimized, the efficiency of the thermoacoustic refrigeration system can be maximized. For future work, the relationship between the wave distortion and the pressure of the acoustic wave inside the resonator should be done and it may help to gain more understanding about the wave distortion characteristic.

5.2 Recommendation for The Future Study

Some recommendations for future studies to improve the understanding of the thermoacoustic refrigeration system have been suggested in this subsection. Firstly, other elements need to be considered for running this research, such as the vibration of the resonator and the speaker. The vibration inside the resonator needs to be checked and to study. The vibration may affect the result, and a suitable insulator needs to be proposed in improving the thermoacoustic system.

Next, the pressure of the acoustic wave inside the resonator that been produced by the speaker. The pressure is also the main element that may be disturbing the effectiveness of the results that have been gathered. To see the wave distortion without knowing the actual pressure inside is difficult because we cannot see the relationship between the pressure and the velocity of the wave. From my understanding, the wave distortion can see when we manage to see the reduction of the wave velocity in linear motion inside the resonator and the increase of the pressure in the resonator.

Understanding the wave properties is important because when we manage to fully utilize the behavior of the wave that has been used in the thermoacoustic refrigeration system, we can improve the efficiency of the thermoacoustic refrigeration system. Other than that, we also can provide a better design because we can reduce the unnecessary elements that are disturbing the system.

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APPENDIX

APPENDIX I: Gantt chart for PSM 1

	Weeks / Activity	1	2	3	4	5	6	7	MID TERM BREAK	9	10	11	12	13	14	15	16
1	Literature review																
2	Determination of objective and scope																
3	Determination of design parameter																
4	Design a simple test rig																
5	Fabrication of the simple test rig																
6	Writing report PSM 1																
7	Slide preparation for Seminar PSM 1																
8	Seminar PSM 1																