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**Performance Mapping of A Two-Stage Travelling Wave
Thermoacoustic Engine for Heat Recovery**

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ABSTRACT

This thesis describes the characterization of the performance of a Two-Stage Travelling Wave Thermoacoustic Engine, called the DEMO 2 Engine. Preliminary experiments on the DEMO 2 Engine showed that its performance level was far below its design expectations. Thus, an analytical approach was developed to investigate the sources of losses that were affecting the performance of the DEMO 2 Engine. The approach involves studying the heat transfer and acoustic performance of the DEMO 2 Engine as well as constructing a numerical model of the DEMO 2 Engine.

Consequently, a heat flow chart was constructed to investigate the heat flow across the individual components in the DEMO 2 Engine. Also, the Four Microphone Impedance Tube Method was modified to enable the determination of the Transfer Matrix for the components in the DEMO 2 Engine. The effects of heat input on the Transfer Matrix of the DEMO 2 Engine's Thermoacoustic Core was also investigated. Apart from that, a numerical model was constructed and validated with experimental observations. Subsequently, the model was able to carry out further investigations on the DEMO 2 Engine where experimental investigations are unable to do so.

As a result, the losses affecting the DEMO 2 Engine was successfully identified. The losses were also characterized quantitatively such that each of its effect could be compared with each other.

LIST OF PUBLICATIONS

JOURNAL

- J. H. Goh, Y. A. Abakr, and D. B. Hann, “Influence of Feedback Loop Characteristics on the Performance of A Travelling Wave Thermoacoustic Engine,” *Fundamental and Applied MHD, Thermo Acoustic and Space Technologies*, 2014, vol. 1, pp. 423–427.

CONFERENCE PAPER

- J. H. Goh, Y. A. Abakr, and D. B. Hann, “Influence of Feedback Loop Characteristics on the Performance of A Travelling Wave Thermoacoustic Engine,” in: 9th PAMIR International Conference. Fundamental and Applied MHD: Thermoacoustic and Space Technologies, 16th – 20rd June 2014, Riga, Latvia.

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ABBREVIATIONS

2MWDM	Two- Microphone Wave Decomposition Method
AHX	Ambient Heat Exchanger
CFD	Computational Fluid Dynamics
DELTA EC	Design Environment for Low-amplitude Thermoacoustic Energy Conversion
FMITM	Four Microphone Impedance Tube Method
HHX	Hot Heat Exchanger
LTAT	Linear Thermoacoustic Theory
MMWDM	Multi Microphones Wave Decomposition Method
PSD	Power Spectral Density
PVC	Polyvinyl chloride
SCORE	Stove for Cooking, Refrigeration and Electricity
SWR	Standing Wave Ratio
TA	Thermoacoustic
TAE	Thermoacoustic Engine
TBV	Thermal Buffer Volume
TD	Temperature Difference

NOMENCLATURE

β	Thermal expansion coefficient
$\% \eta_{Carnot}$	Percentage of Carnot efficiency
$\emptyset$	Volumetric porosity
A	Area
A_{wetted}	Wetted area
c	Speed of sound
c_p	Specific heat capacity of gas
$\dot{E}$	Acoustic power
F	Force
f	Frequency of the soundwave
$F_{continuity}$	Continuity function
$F_{momentum}$	Momentum function
f_v	Spatially averaged visocus function
f_κ	Spatially averaged thermal function
g	Acceleration due to gravity
h	heat transfer coefficient
h_v	Thermoviscous function
i	$\sqrt{-1}$
K	Thermal conductivity
L_c	Characteristic length
$\dot{m}$	Mass flow rate of the cooling water
N_L	Lautrec Number
Nu	Nusselt number
P_A	Pressure measured at pressure transducer A

P_B	Pressure measured at pressure transducer B
P_C	Pressure in the compliance
P_{in}	Pressure at the inlet
P_{mid}	Pressure at the midpoint of the pressure transducers
Pr	Prandtl number
$\dot{Q}_{acoustic}$	Acoustical power generated by the TA Core
$\dot{Q}_{heater}$	Heat input rate from the electrical heater
$\dot{Q}_{in}$	Total heat input rate
$\dot{Q}_{loss}$	Total rate of heat loss to the surroundings
$\dot{Q}_{natural\ convection}$	Rate of heat loss through natural convection
$\dot{Q}_{parasitic\ loss}$	Total rate of parasitic heat losses
$\dot{Q}_{rejected}$	Heat rejected rate at the AHX
R	Reflection coefficient
RA_L	Rayleigh Number
r_h	hydraulic radius
S_{11}	Reflection coefficient at 1
S_{12}	Reverse gain from 1 to 2
S_{21}	Forward gain from 1 to 2
S_{22}	Reflection coefficient at 2
SWR_{in}	Standing Wave Ratio entering 1
SWR_{out}	Standing Wave Ratio exiting 2
$T_{ambient}$	Ambient temperature
T_C	Temperature of the cold reservoir of a Carnot Engine
T_f	Film temperature
T_H	Temperature of the hot reservoir of a Carnot Engine
T_{inlet}	Temperature of the water at the inlet of the AHX
T_m	Mean temperature

T_{outlet}	Temperature of the water at the outlet of the AHX
$T_{surface}$	Surface temperature
u	x component of velocity
U_C	Volume flow rate into the compliance
U_{in}	Volume flow rate at the inlet of the load
U_{mid}	Volume flow rate at the center of the two pressure transducers
v	Particle velocity
V_{gas}	Pores volume
$\dot{W}_{out}$	Work output rate
Z	Impedance
z_0	Characteristic specific acoustic impedance
α	Absorption coefficient
γ	Ratio of isobaric to isochoric specific heat
δ_k	thermal penetration depth
η	Ratio of the useful work output rate to the total heat input rate
η_{Carnot}	Carnot efficiency
η_{max}	Maximum efficiency
θ	Phase difference between the pressure and velocity
κ	Thermal conductivity of gas
λ	Wavelength
ν	Kinematic viscosity
ρ	Density of gas
ρ_m	Mean density of the fluid
ω	Angular frequency of gas oscillation

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CHAPTER 1

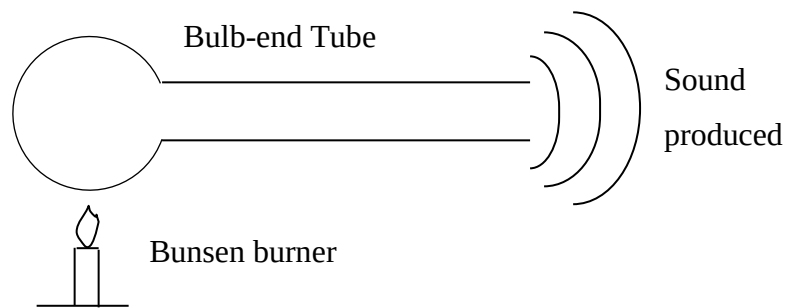
INTRODUCTION

1.1 Thermoacoustic Overview

Thermoacoustic is a phenomenon that involves using heat transfer to produce sound wave and vice versa. One of the earliest recorded observations of the thermoacoustic phenomenon took place when glass blowers attached a hot glass bulb to a cool glass tube and noticed a humming sound. This phenomenon was successfully replicated by Sondhauss in an experiment set up that is now known as the “Sondhauss Tube” [1]–[3], as shown in Figure 1.1 (a). Independently, Rijke also demonstrated the thermoacoustic effect while researching on pipes for musical instruments [1], [2]. Rijke’s experiment set up is shown in Figure 1.1 (b) and is now known as the “Rijke Tube” [3]. However, both Sondhauss and Rijke did not explained the cause of the thermoacoustic effect. The first qualitative explanation of the thermoacoustic effect was stated by Lord Rayleigh in “The Theory of Sound” that heating and cooling air can produce acoustic power *“if heat be given to the air at the moment of greatest condensation, or be taken from it at the moment of greatest rarefaction”* [4]. This statement has become the Rayleigh criterion that explains the fundamental principle of

thermoacoustic, while both the Sondhauss and Rijke Tube continues to be a useful demonstration of the thermoacoustic phenomenon.

a) Sondhauss Tube



b) Rijke Tube

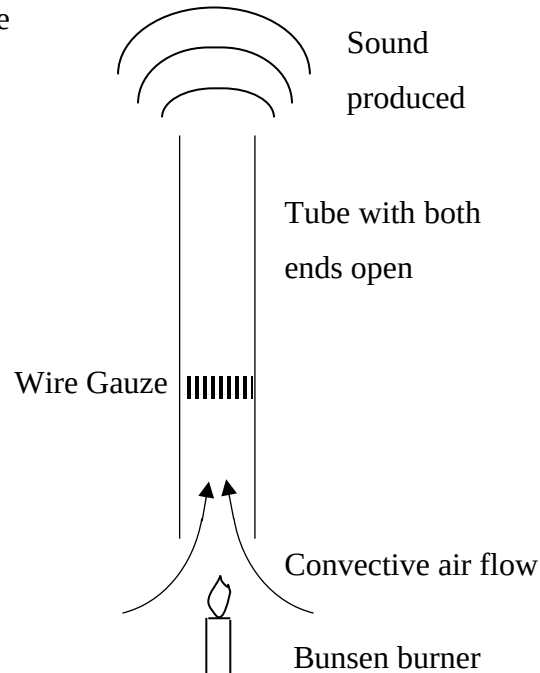


Figure 1.1: (a) Illustration of the Sondhauss Tube experiment. (b) Illustration of the Rijke Tube experiment.

A later observation of the thermoacoustic phenomenon was made by Taconis in the field of cryogenics when one end of a tube was submerged in liquid helium and the other end was left in room temperature and sound oscillation was produced [5]. This observation is then named the “Taconis Oscillations” and is generally an undesired effect in cryogenics as it will affect the accuracy of measuring devices. Then, in the analysis of the Taconis Oscillation, Rott derived the mathematical equations that describes the criterion when the Taconis Oscillations would occur. Consequently, Rott’s description provided the first quantitative explanation of the thermoacoustic phenomenon and it is now known as the Linear Thermoacoustic Theory (LTAT) [6]–[10].

Despite of these developments, the oscillations produced by the examples stated above were not powerful enough for significant application. It was until 1970 that Carter improved on the Sondhauss Tube by inserting a stack into the tube and greatly increased the acoustic power output [11]–[13]. The stack is made of a porous medium and it will be explained in more details in the following sections. The improvements made by Carter showed the potential of using thermoacoustic for design of heat engines and heat pumps. Another significant breakthrough was made with the realization by Ceperley that the phase between the volume and pressure fluctuations of the gas in the regenerator of a Stirling Engine is the same as a travelling wave [14]. Both Carter’s and Ceperley’s work has led to the development of Standing Wave and Travelling Wave Thermoacoustic Engines, respectively. The main difference of these two classes of

Thermoacoustic Engines is the use of a stack or regenerator to generate work output. The criteria to differentiate between a stack or a regenerator is explained in the next section.

1.1.1 Stack and Regenerator

In a Thermoacoustic Engine (TAE), the Stack or the Regenerator is the porous medium that provides the temperature gradient for the working gas to accept and reject heat to complete its thermodynamic cycle. The criteria to differentiate between a stack or a regenerator is its Lautrec Number, N_L [15], [16]. If $N_L \gtrsim 1$, then the porous medium is a stack and if $N_L < 1$, then the porous medium is a regenerator. The Lautrec Number is the dimensionless ratio of hydraulic radius, r_h , to thermal penetration depth, δ_k . The hydraulic radius, r_h , of the porous medium is the ratio of its pores volume, V_{gas} , to its wetted area, A_{wetted} [17]. The thermal penetration depth, δ_k , is defined as the distance that heat can diffuse through an oscillating gas, and it is equals to $(2\kappa/\rho c_p \omega)^{1/2}$, where κ is the thermal conductivity of the gas, ρ is the density of the gas, c_p is the specific heat capacity of the gas, and ω is the angular frequency of the gas oscillation. Hence, the Lautrec Number, N_L indicates how good the thermal contact between the porous medium and the working gas is.

The Standing Wave Thermoacoustic Engine uses a stack and the Travelling Wave Thermoacoustic Engine uses a regenerator. These are so that the temperature gradient along the stack and regenerator would provide a temperature oscillation to the working

gas that couple with the phasing of a Standing Wave and Travelling Wave respectively to meet the Rayleigh criterion for acoustic power generation. The working principles and differences of the Standing Wave Thermoacoustic Engine and Travelling Wave Thermoacoustic Engines are explained in the following sections.

1.1.2 Standing Wave Thermoacoustic Engine

The simplest demonstration of a Standing Wave Thermoacoustic Engine is the Sondhauss Tube experiment, shown in Figure 1.1 (a). A tube with one end open and another end closed is heated by a Bunsen burner at the closed end, causing a temperature gradient along the wall of the tube [1]. The original Sondhauss experiment used a glass tube with a bulb end, but a properly designed straight tube could also achieve the same effect.

For acoustic power generation, the dimensions of the tube and the rate of heating must be designed to meet the Rayleigh criterion. When a sound wave oscillates in a tube with one end closed and another end open, the air at the closed end will not be able to oscillate and the air at the open end will oscillate freely. Hence, the air at the closed end experience the highest pressure and the air at the open end experience the lowest pressure. The displacement and pressure distribution along the length of the tube is shown in Figure 1.2. A tube with such configuration is referred as a Quarter Wave Tube as the length of the tube is a quarter of the wavelength of its natural frequency [18]. Therefore, the Quarter Wave Tube provides the acoustic environment for a standing

wave to oscillate. Besides that, the diameter of the Soundhauss Tube is much larger than the thermal penetration depth of the air so that there is a temperature difference between the wall and the air parcel adjacent to it, as shown in Figure 1.2. As the air parcel moves towards the closed end, it experiences an increasing pressure and its temperature is lower than the walls of the tube, hence it gains heat from the tube. In contrast, when the air parcel moves towards the open end, its pressure is decreasing, and its temperature is higher than the walls of the tube, hence it rejects its heat to the tube [19]. Therefore, the Rayleigh criterion is met, and sound oscillation is produced.

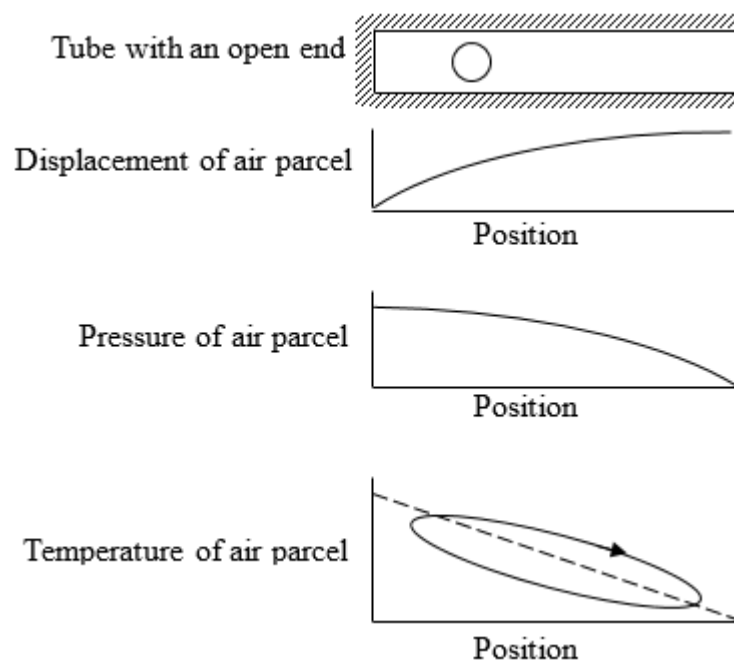


Figure 1.2: Displacement, pressure and temperature of the air parcel versus position in a quarter wave tube. The dashed line indicates the temperature of the wall and the arrow indicates the direction of the parcel of air oscillating in time.

When Carter inserted a “stack” into the tube, the intensity of the sound oscillation produced increased vastly. The stack is a porous material that consists of many parallel channels. Some simple examples of constructing stacks are bundling many straws together or lining parallel plates together. Every channel in the stack works like a single Sondhauss tube and together they are able to produce significant acoustic power. In a Standing Wave TAE, the stack is placed in a resonator. The resonator is carefully designed to provide a Standing Wave acoustic environment for the operating gas to oscillate. When one end of the stack is heated while the other end is cooled, a standing wave will be produced in the resonator. An imperfect thermal contact between the walls of the stack and the gas is needed to satisfy the Standing Wave phasing and the Rayleigh criterion, as shown in the Sondhauss oscillations example. Due to this, the thermal efficiency of the standing wave engine is limited and the best thermal efficiency achieved is approximately 20% only [20]. Despite that, the motivation to use a standing wave engine [21]–[26] is it is simple and generally cost less to build.

1.1.3 Travelling Wave Thermoacoustic Engine

For a Travelling Wave, the pressure oscillation of the air is in phase with its velocity oscillation, as illustrated in Figure 1.3. In a Travelling Wave Thermoacoustic Engine, a regenerator is used instead of a stack and excellent thermal contact between the gas and the regenerator is required. An example of building a regenerator is by stacking layers of wire mesh together. The temperature, pressure and volume oscillation of the

working gas at various position and instances in the regenerator is also illustrated in Figure 1.3 [15].

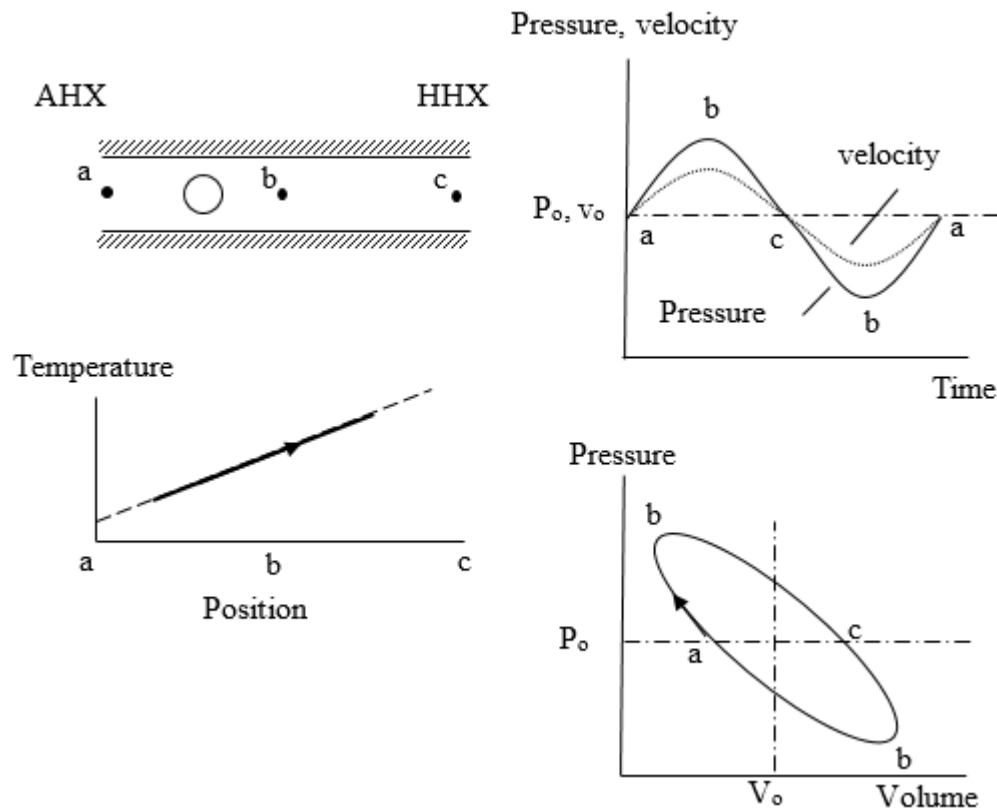


Figure 1.3: The temperature, pressure and volume oscillation experienced by a parcel of air in a channel of the regenerator of a Travelling Wave Thermoacoustic Engine.

Due to the excellent thermal contact between the gas and the regenerator, the temperature of the gas is the same as the temperature of the solid walls of the regenerator. Referring to Figure 1.3, at position “a”, the gas parcel is undergoing a compression while its pressure is increasing. As the gas moves from “a” to “b”, it

rejects heat to the regenerator while its pressure continues to increase to the maximum and its volume continues to be compressed to its minimum. From “b” to “c”, the gas volume starts to expand, and its pressure begins to decrease. Also, the gas begins to accept heat from the regenerator. These continues as the gas movement changes direction and moves back from position “c” to “b”. At this instant, the gas volume has expanded to its maximum and its pressure has decrease to its minimum. When the gas travels back from “b” to “a”, it begins to reject heat to the regenerator and undergo a compression while its pressure increases. An Ambient Heat Exchanger (AHX) and Hot Heat Exchanger (HHX) is needed at the ends of the Regenerator to force the gas to undergo the desired temperature oscillation. The Regenerator acts as a “temporary heat storage” medium for the gas while it completes its thermodynamic cycle as shown in Figure 1.3. Due to the good thermal contact between the gas and the regenerator, the Travelling Wave Thermoacoustic Engine is theoretically more efficient than the Standing Wave Thermoacoustic Engine. However, it is much more complex to be designed and manufactured as it requires an acoustic network to provide the necessary environment for a travelling wave. Despite that, many examples of Travelling Wave Thermoacoustic Engine were successfully built and showed its potential for wider applications [27]–[33].

1.2 Research Background

In 2007, the Stove for Cooking, Refrigeration and Electricity (SCORE) Project was established to address the energy shortage issues of people living in rural areas [34].

The SCORE Project aims to design a low-cost cooking stove that is able to capture waste heat from wood or biomass fire and convert it to electricity. To achieve this, the SCORE project will incorporate a TAE onto a cooking stove and converts the waste heat energy to sound wave and a Linear Alternator will then convert the sound wave to electricity [35]. The design requirements for the SCORE Stove are to generate 150 Watts of electricity, cost less than £20 to manufacture and weigh approximately 10 to 20kg [36].

Under the SCORE Project, the advantages and limitations of both Standing Wave and Travelling Wave TAE were evaluated [37], [38]. Although Standing Wave TAE is more simple and cheaper to manufacture, it is often required to operate at a high acoustic pressure. This is to overcome the engine's lower efficiency deficit and still achieve the required power output. At this high acoustic pressure, it is not feasible to design a Linear Alternator that can withstand the pressure and able to meet the physical constraints. Therefore, it is concluded that a Travelling Wave TAE is more suitable to achieve the SCORE Project's objectives [38].

The higher heat efficiency of a Travelling Wave TAE is the main advantage over Standing Wave TAE. Backhaus and Swift [39] have developed a Travelling Wave TAE with an efficiency of 42% of Carnot efficiency. This TAE has its regenerator placed in a toroid tube connected to a resonance tube. The high efficiency was recorded at an operating temperature of 725°C and the gas used was helium. These conditions are

hardly feasible for low cost applications, as required in the SCORE Project. The proposed solutions to this problem have led to the development of a multi-stage Travelling Wave TAE. The Temperature Difference (TD) between the cold surface and hot surface of the Thermoacoustic Core when oscillations begin is denoted as the Onset TD. Biwa et al. [40] showed that increasing the number of regenerators in the TAE is able to reduce the Onset TD, but this will reduce the TAE efficiency as more heat has to be supplied to the added regenerators. De Blok's design of a 4-stage Travelling Wave TAE has achieved an Onset TD of 30K [41]. This TAE has 4 regenerators connected via a Feedback Loop, as shown in Figure 1.4. The 4 regenerators are positioned a quarter wavelengths apart to allow the Feedback Loop to have an impedance self-matching capability, similar to the working principle of a quarter wave impedance transformer [42]. A mismatch of impedance along the system will cause reflection of the wave [43].

The SCORE Project adopted the design by De Blok and developed a Dual Regenerator Travelling Wave TAE, named the DEMO 2 Engine [36]. The design and operating conditions of the DEMO 2 Engine is described in the next section.

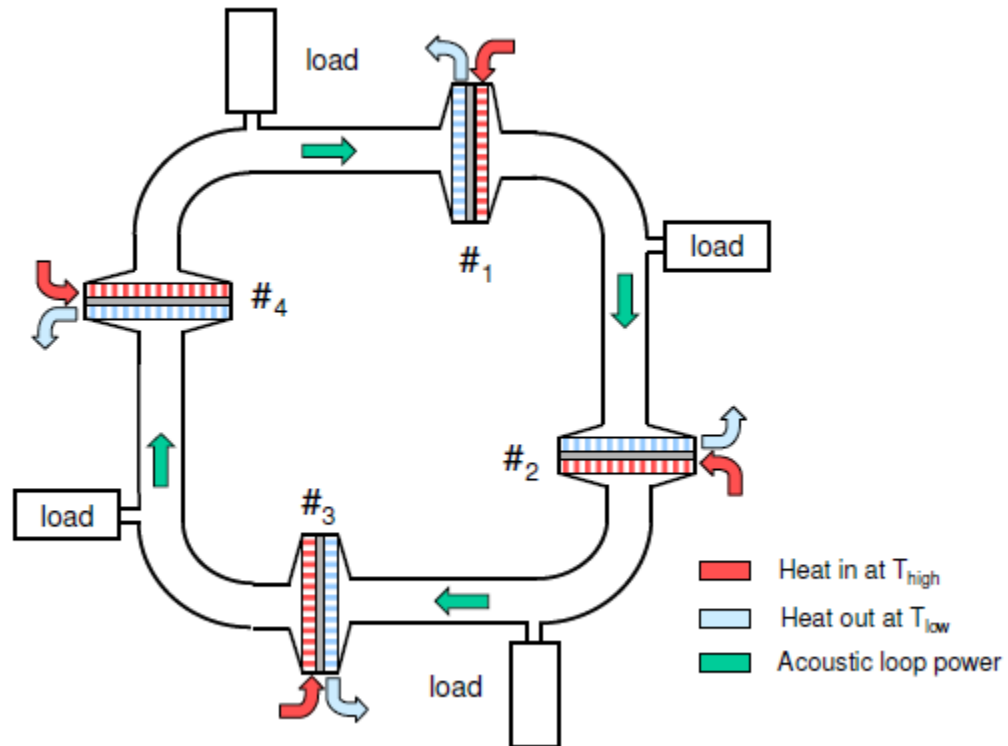


Figure 1.4: Schematic diagram of a 4-stage travelling wave TAE designed by Aster Thermoakoesische Systemen. The red and blue rectangles are the hot and cold heat exchangers, respectively [44].

1.2.1 SCORE DEMO 2 Engine

The DEMO 2 Engine consists of two TA Cores connected by a Feedback Loop, as shown in Figure 1.5. Both TA Cores are almost identical and are made of a Regenerator clamped in between the HHX and the AHX. Having two regenerators is sufficient to lower the expected Onset TD to a range that can be provided by wood burning without compromising the efficiency of the TAE excessively. Each regenerator is made of 40 pieces of Stainless Steel Wire Mesh, the HHX is a custom-made Stainless-Steel plate

with a convoluted profile and the AHX is a custom-made car radiator. The frame of the TA Core was deliberately designed to be larger to accommodate a space between the AHX and the Feedback Loop to act as a Tuning Volume. Various materials could be added into the Tuning Volume to change the total volume of air in the TA Core which would change the impedance of the TA Core. Besides that, there is a cavity named the Thermal Buffer Volume (TBV) that delays the heat transfer from the hot air in the HHX to the Feedback Loop.



Figure 1.5: The DEMO 2 Engine driven by electrical heaters.

A schematic diagram of the components inside the TA Core is shown in Figure 1.6 and a detailed description of the TA Core can be found in previously published work by the SCORE project [45]–[47]. The DEMO 2 Engine was designed to be used on a wood burning stove, however, for experimental purposes, an electrical heater was used as a

heat source instead as it is much easier to control than a fire from burning wood. The electrical heater is placed in an insulated box and heats the HHX while the AHX is cooled by running water at room temperature of approximately 28°C [45].

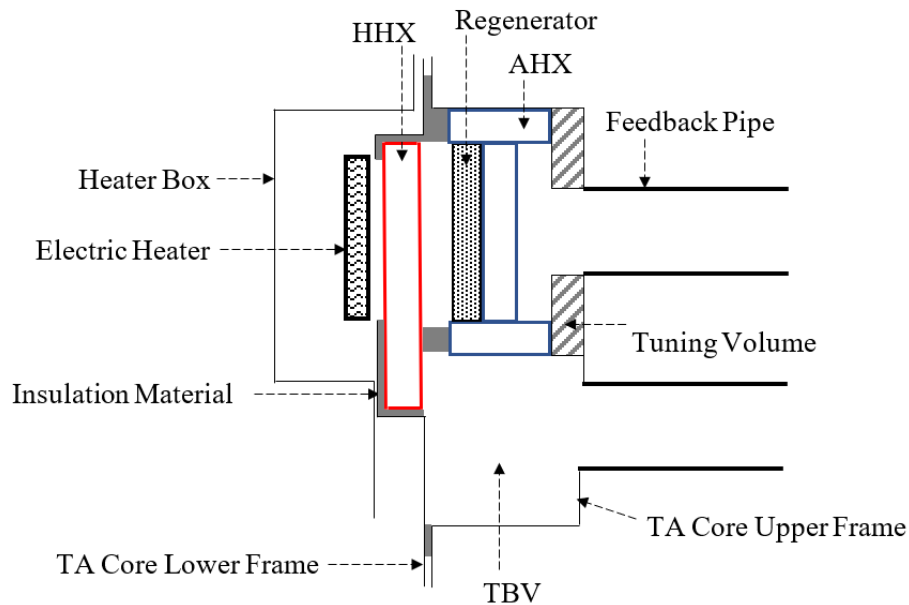


Figure 1.6: A schematic diagram of the TA Core. Illustration is not to scale.

Upon assessment of the DEMO 2 Engine performance [48], it is found that the performance of the DEMO 2 Engine did not meet the expectations of the design. This is evident by the low generation of peak pressure by both Thermoacoustic Core 1 and Core 2, which is insufficient to meet the power output requirement of the Engine. The maximum peak pressure recorded for Thermoacoustic Core 1 and Thermoacoustic Core 2 is 1,316 Pa and 1,589 Pa, respectively. On the other hand, the lowest onset temperature recorded by the DEMO 2 are 124°C at Thermoacoustic Core 1 and 161°C

at Thermoacoustic Core 2. Besides that, there are uncertainties on the performance of the Feedback Loop to eliminate the reflection as well as the effect of possible parasitic volumes. These highlighted issues raise concerns on the ability of the Feedback Loop to provide the acoustic environment for a travelling wave to propagate. Therefore, further investigation is necessary to optimize the DEMO 2 Engine's performance. The factors affecting the sound power generation of a Thermoacoustic Engine need to be investigated.

1.3 Problem Statements

From the assessment of the DEMO 2 Engine, it was evident that there is no clear understanding on the reason for its poor performance and a systematic approach is needed to analyze the DEMO 2 Engine, especially during its operation. Consequently, the problems encountered were summarized as below:

- Factors that could affect a TAE is not well understood, and this could potentially lead to a poorly designed engine.
- During the operation of a TAE, it is very challenging to investigate the phenomena within the TA Core. Hence, it is very challenging to investigate any potential factors that are affecting the TAE.
- Due to design constraints, features that are known to have harmful effects to the propagation of a soundwave in a duct is unavoidable. However, there is no quantitative explanation of the effects of such features to a TAE. With a quantitative

description, designers could incorporate such features with minimal effect to the TAE.

1.4 Research Questions

Based on the problem statements depicted in Section 1.3, the research questions for this study are raised as following:

- What are the factors that could affect the performance of a TAE?
- How to identify and subsequently quantify these factors?
- What methods could be used to investigate the phenomena inside a TA Core during its operation?

1.5 Project Aim and Objectives

The aim of this PhD project is to provide a detailed and quantitative assessment on the factors that are affecting the performance of a TAE. This will subsequently aid in determining the significance and impact of each factor that is affecting the performance of the TAE. Consequently, this would also improve the understanding on the characteristics of the TAE performance.

To accomplish this, the following objectives are set for this PhD project:

- To identify the source of losses that affects the TAE performance.

- To construct a numerical model for the TAE. The model will be validated by experimental data.
- To perform parametric studies on a 2 Stage Travelling Wave TAE in a closed loop.
- To obtain the optimum parameters for the TAE with the numerical model.

In this study, the DEMO 2 Engine was used to perform the investigation studies throughout the entire research work.

1.6 Research Contributions

The contributions of this project not only benefit the development of the DEMO 2 Engine, but also benefit the research community by providing the following:

- Provide a systematic approach to assess the performance of a TAE.
- Provide a validated approach to construct a numerical model of a TAE.
- Provide a quantitative description on the type of losses which could occur in a TAE.

1.7 Thesis Outline

In the previous sections, the background to this project was defined, along with the corresponding aims and objectives of the project as well as the research contributions.

Set against this background, a detailed literature review is performed on the thermodynamics and acoustic theories appropriate to this project in CHAPTER 2 to

deliver the background information. Here, reviews on the experimental analysis and measurement techniques employed to rate the performances of TAEs are presented, followed by the reviews on the techniques applied in the numerical modelling of TAEs.

Accordingly, an overview of the work flow of this project as well as the research methodology used in this project is presented in CHAPTER 3. This Chapter covers the discussion on the rectifications made to the DEMO 2 Engine to improve the experimental investigations as well as the types of measurement taken to analyse the DEMO 2 Engine performance.

In CHAPTER 4, heat flow analysis is carried out to compute the heat flow network. Subsequently, evaluation of the acoustic performance and numerical modelling of the DEMO 2 Engine are performed according to the results obtained from the heat flow analysis.

Next, in CHAPTER 5, the two key features affecting each of the acoustic component in the DEMO 2 Engine are determined, namely the effective length and change in acoustic impedance.

In CHAPTER 6, the measurement techniques adopted to obtain the Transfer Matrix of the acoustic components in the DEMO 2 Engine are presented. Apart from that, the

effects of the presence of heat input to the DEMO 2 Engine on the Transfer Matrix are also examined.

Successively, the DELTA EC model is generated, and the process is described in CHAPTER 7. The model predictions of the conditions in the Feedback Loop are compared against the experiment results.

Lastly, the overall evaluations of the research work reported in this project are summarised in CHAPTER 8. Key conclusions from the research studies are highlighted and some recommendations for further work are presented too.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Although the thermoacoustic phenomenon was noticed for more than hundred years ago, extensive research on thermoacoustic heat engines and pumps only begin during the 1970s following the contributions by Carter and Ceperley [49] that led to the invention of the Standing Wave and Travelling Wave TAEs, respectively. Despite that, the field of thermoacoustic comprises of thermodynamics and acoustics, both of which are well-known and well-researched fields. Hence, research in thermoacoustic benefits greatly from the knowledge gained from thermodynamics and acoustics, while developing theories of its own as it progresses. In this chapter, the thermodynamics and acoustic theories relevant to this project is being reviewed. The literature review in this chapter is divided into two parts. The first part reviews the experimental analysis and measurement techniques used to rate the performances of TAEs. Subsequently, the second part reviews on the techniques used for numerical modelling of TAEs. A summary is provided at the end of each part and the techniques that suit the objectives of this project is stated.

2.2 Experimental Analysis of TAEs

To rate the performance of a TAE, many types of measurements were taken depending on the application of the TAE as well as the main attribute of interest [50]. For example, if a TAE is needed as the driver to a thermoacoustic refrigerator, then the characteristics of its acoustic output is of main interest to ensure it is able to provide the optimum operating conditions for the refrigerator. In contrast, the TAEs designed under the SCORE Project is focused on a low-cost solution for heat recovery. Thus, evaluation of the TAE cost effectiveness and efficiency is of main interest. For the DEMO 2 Engine, its fabrication cost has been evaluated during the designing process and its final fabrication cost was determined in previous work. Set against this background, the types of measurements being used to rate TAEs is being reviewed and the relevant measurements required for this project is highlighted in Section 2.2.1. It is worth mentioning that the significances of the measurement types along with the associated problems encountered during measurements are first presented in this section. This is followed by the theoretical backgrounds of the corresponding measurement parameters in Section 2.2.2. Here, governing equations of the theory applied are provided to explain and support the investigation studies conducted throughout the research work. In Section 2.2.3, the summary on the experimental analysis of TAEs is presented.

2.2.1 Types of Engine Performance Measurements

The most straightforward measurement to rate the performance of a heat engine is to measure its power output, which is often defined as the rate of the useful work output.

For a TAE, the useful work output is its acoustic work and hence measuring its acoustic power output is of interest. However, in the DEMO 2 Engine, the acoustic power output is not the final power output. The DEMO 2 Engine is designed as a heat recovery system. Hence, it is required to capture waste heat and convert it to acoustic energy through the thermoacoustic effect and finally the acoustic energy is converted to electrical energy. However, the objective of this project is to investigate on the sources of loss that are affecting the acoustic power output of the DEMO 2 Engine. Thus, the conversion of acoustic energy to electrical energy is beyond the focus of this project.

In addition to measuring the power output of a TAE, determining its efficiency also provides an indication of how well the TAE is performing. It is noted that heat transfer and energy conversion processes take place in more than one location during the operation of the DEMO 2 Engine. Therefore, simply taking the final power output and efficiency is not sufficient to identify and quantify the sources of losses that is affecting the DEMO 2 Engine performance. Instead, the power output and efficiency at every component has to be determined in order to identify the component that has the largest effect on the overall performance. To accomplish this, a power flow chart is needed to map out the path of the heat transfer and conversion from the initial heat source to the final output [51].

Furthermore, besides heat losses in the TAE, acoustic losses also play a significant role in reducing the performance level of the TAE. This is even more evident for a

Travelling Wave TAE as designing its acoustic network is very challenging. To analyze the acoustic network of a TAE, the characteristics of the soundwave produced by the TAE is required to be determined first with the use of wave decomposition method. Subsequently, the acoustic properties of the engine components are determined by obtaining its Transfer Matrix.

2.2.2 Theoretical Backgrounds of the Measurement Parameters

According to the performance measurement types illustrated in the previous section, the associated governing equations applied in each of the measurement technique to rate the performance of TAE in terms of power output, efficiency, and acoustic losses are presented in this section.

2.2.2.1 Power Output

While sound wave generated by the TAE is contained in its resonator or acoustic network, the methods to measure acoustic power in waveguides could be used. To accomplish this, there are two widely-used methods to accurately determine the acoustic power in a waveguide. The first method is to attach an acoustic load to the waveguide and measure the power dissipated across the load. For higher accuracy from this method, a variable acoustic load could be used instead to record multiple observations. An example of a variable acoustic load is to connect a volume of air through a valve to the TAE acoustic network, as shown in Figure 2.1. The volume of

air act as a compliance and the connection pipes and valve act as a resistance. By turning the valve, the resistance of the load changes, hence it works as a variable load.

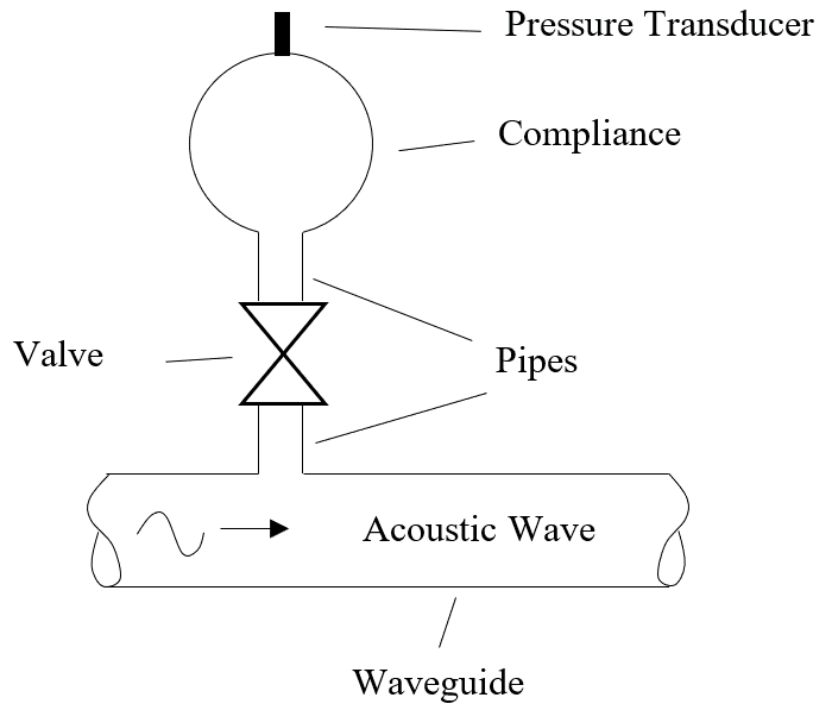


Figure 2.1: Illustration of a variable load connected to a waveguide.

By measuring the pressure in the compliance, P_C , using a pressure transducer, the Volume Flow Rate into the compliance, U_C , can be obtained by

$$U_C = \frac{i\omega V}{\gamma\rho_m} P_C \quad (2-1)$$

where i is $\sqrt{-1}$, γ is the ratio of isobaric to isochoric specific heat and ρ_m is the mean density of the fluid.

If the volume of the pipes could be ignored, then the Volume Flow Rate at the inlet of the load, U_{in} is equals to U_C . In addition, if the wave propagating in the waveguide is assumed to be plane wave, then the pressure at the inlet, P_{in} , can be measured by attaching another pressure transducer to the waveguide at the same axial location. Therefore, the acoustic power, $\dot{E}$, dissipated by the load can be determined by:

$$\dot{E} = \frac{1}{2} \text{Re} [P_{in} \tilde{U}_{in}] \quad (2-2)$$

The second method to measure the acoustic power in a waveguide is the two-microphone method [52]–[56], as illustrated in Figure 2.2. This method is used to determine the acoustic power at the midpoint of the microphones pair. Despite the name of this method, pressure transducers could also be used. By assuming plane wave propagating in the waveguide, the pressure at the midpoint of the pressure transducers, P_{mid} equals to the average of both pressure transducers:

$$P_{mid} = \frac{P_A + P_B}{2} \quad (2-3)$$

where P_A and P_B is the pressure measured at pressure transducers A and B, respectively.

Similarly, the particle velocity, v of the sound wave propagating in the waveguide can be obtained through the pressure gradient between two locations:

$$v = \frac{-1}{\rho} \int \frac{dp}{dx} dt \quad (2-4)$$

where ρ is the density of air and t is the time. If the sensor separation distance is much smaller than the wavelength of the sound wave, then the sound attenuation due to the waveguide can be neglected and the pressure gradient in Equation (2-4) can be taken as the spatial average between the two pressure transducers using Euler's Equation [57]–[61]. Hence, the volume flow rate at the center of the two pressure transducers, U_{mid} , can be determined by:

$$U_{mid} = -\frac{A}{\rho} \int \frac{P_A - P_B}{\Delta x} dt \quad (2-5)$$

where A represents the area.

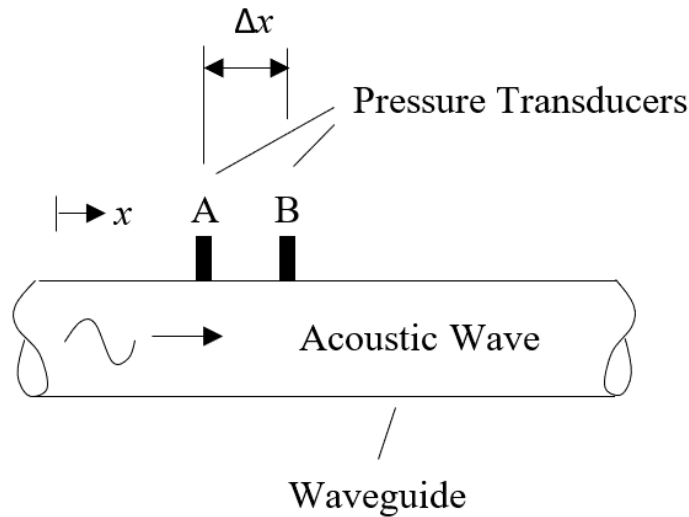


Figure 2.2: Illustration of the two-microphone method.

Therefore, the acoustic power at the midpoint of the two pressure transducers can be obtained from Equation (2-2) by replacing the inlet conditions with the midpoint conditions.

2.2.2.2 Efficiency

The efficiency of a system, η is the ratio of the useful work output rate, $\dot{W}_{out}$, to the total heat input rate, $\dot{Q}_{in}$.

$$\eta = \frac{\dot{W}_{out}}{\dot{Q}_{in}} \quad (2-6)$$

For a TAE, the useful work output is the acoustic work. Thus, the acoustic power output determined by the methods discussed in Section 2.2.1 can be used in Equation (2-6). Apart from that, methods to measure $\dot{Q}_{in}$ depends on the TAE design. For the DEMO 2 Engine, the heat input source is an electrical heater, therefore the power dissipated by the electrical heater can be obtained by calculating the product of the Voltage and Current of the power supply circuit. However, $\dot{Q}_{in}$ is the amount of heat input rate into the working gas of the DEMO 2 Engine. Hence, the heat losses from the electrical heater to the working gas must be determined first to obtain $\dot{Q}_{in}$.

Alternatively, the efficiency of a heat engine can also be compared to the Carnot efficiency, η_{Carnot} . The Carnot theorem states that the efficiency of a heat engine cannot exceed the efficiency of a Carnot engine. This theorem can be expressed by

$$\eta_{max} = \eta_{Carnot} = 1 - \frac{T_C}{T_H} \quad (2-7)$$

where T_C and T_H are the temperature of the cold and hot reservoir of a Carnot Engine, respectively. Thus, the efficiency of a heat engine can be expressed in percentage of Carnot efficiency, $\% \eta_{Carnot}$.

$$\% \eta_{Carnot} = \frac{\eta}{\eta_{Carnot}} \times 100 \% \quad (2-8)$$

For a Travelling Wave TAE, the cold and hot reservoir are the cold and hot side of its regenerator, respectively. Therefore, the temperatures of the hot and cold side of the DEMO 2 Engine regenerators have to be measured to obtain the theoretical maximum efficiency. Then, the $\% \eta_{Carnot}$ of the DEMO 2 Engine could be determined.

2.2.2.3 *Acoustic Losses*

The acoustic losses analysis requires the information of the characteristics of the soundwave produced by TAE as well as the acoustic properties of engine components. Therefore, wave decomposition is first performed to determine the soundwave characteristics. Following that, Transfer Matrix is applied to determine the acoustic properties of the engine components.

Wave Decomposition

An important characteristic of a soundwave is its Standing Wave Ratio (SWR) [62]–[64]. The SWR is the ratio of maximum amplitude to minimum amplitude of a soundwave and it is a measure of how much the soundwave resembles a pure standing wave or a pure travelling wave. A standing wave is created by the superposition of two waves travelling in opposite directions. If the amplitudes of both waves are the same and its phase difference is exactly 180° , then its superposition will produce a pure

standing wave. The SWR of a pure standing wave is infinity as illustrated in Figure 2.3. For a pure travelling wave, the SWR equals to 1. In actual applications, it is nearly impossible to have a pure standing or travelling wave. Therefore, the SWR of a soundwave ranges from 1 to infinity and in the acoustic network of a Travelling Wave TAE, the desired SWR is as near to 1 as possible.

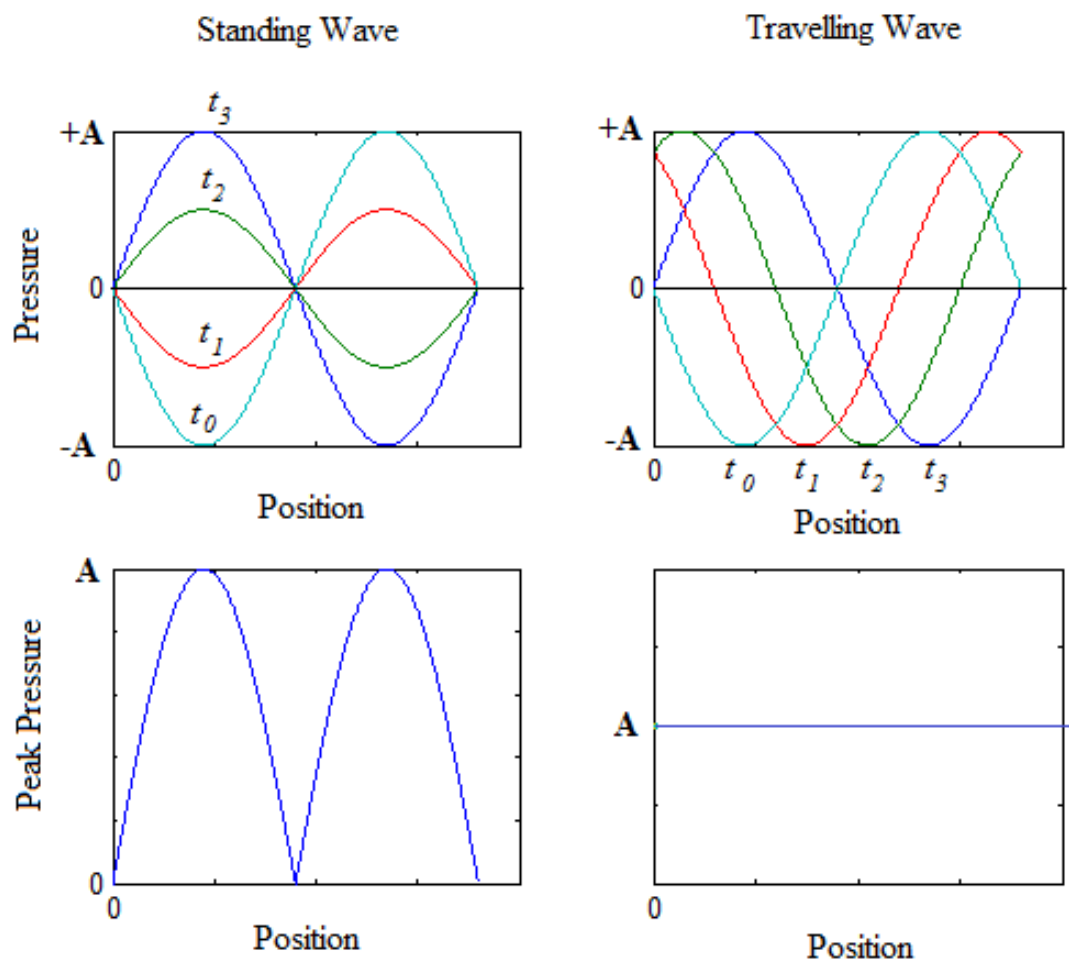


Figure 2.3: Comparison of a pure standing wave and a pure travelling wave at 4 arbitrary time, t .

To measure the SWR of a soundwave propagating in a waveguide, the classical technique used is called the SWR Method [63]. The SWR Method uses a transverse microphone to measure the pressure amplitudes along the axis of the waveguide, as shown in Figure 2.4, and then the ratio between the maximum and minimum pressure amplitude could be determined to obtain the SWR. The disadvantage of the SWR Method is it is time consuming to take a single measurement and the experiment rig is very hard to build [63].

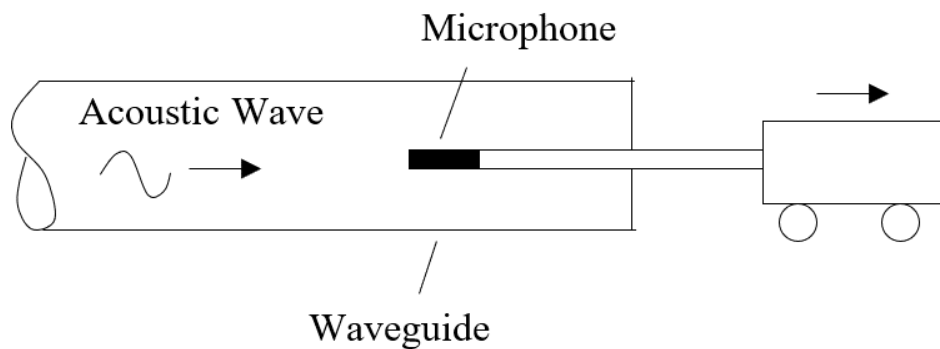


Figure 2.4: Illustration of the SWR Method.

An improved and much convenient method to measure the SWR is the Two-Microphone Wave Decomposition Method (2MWDM) [65]–[67]. The 2MWDM uses a pair of microphones, as shown in Figure 2.2, to decompose a soundwave propagating in a waveguide into its respective components. According to the Fourier Theorem, every wave can be reconstructed by the summation of sine waves, as long as the wave is periodic. The 2MWDM uses Fourier Analysis to decompose the soundwave into its

forward and backward travelling components [68], [69]. With both of these components, the entire soundwave along the waveguide can be reconstructed and hence the maximum and minimum amplitude of the wave can be obtained to determine the SWR. The 2MWDM is much simpler to build and the time taken to make a measurement is much faster than the SWR Method. In addition, the 2MWDM was later expanded to consider the effects of attenuation of the waveguide [70]. Despite that, the 2MWDM has its disadvantages as well. For instance, uncertainty on the measured properties could arise from error in measuring the separation distance of the 2 microphones [71], [72]. Besides that, the suitable frequency range for the 2MWDM is limited (which varies according to the measurement setup) and depends also on its microphones separation distance. To overcome these, the 2MWDM was modified to include measurements from more than 2 microphones in a method called the Multi Microphones Wave Decomposition Method (MMWDM) [73]. The MMWDM performs the wave decomposition with every possible combination of 2 microphones and obtain an average using the least squares method [74]. Hence, the contributions to the measurements uncertainties from a single pair of microphones are minimized.

Transfer Matrix

After the soundwave in the waveguide is decomposed to its forward and backward components, more information besides the SWR could be further extracted. In fact, the 2MWDM was developed to determine the Impedance, Z , Absorption Coefficient, α , and Reflection Coefficient, R , of an absorption material located at the end a waveguide.

A further modification to the 2MWDM suggested by Chung and Blaser [65], [66] is to add a third sensor downstream to the sample to measure the Transmission Coefficient, T , across the sample. Further expanding on this, the Four Microphone Impedance Tube Method (FMITM) was developed to determine a Transfer Matrix for an acoustic material to obtain its acoustic properties [75], [76].

The FMITM involves mounting a pair of microphones at the upstream as well as the downstream to an acoustic material, as shown in Figure 2.5. Then, using the 2MWDM, the forward and backward components of the soundwave was decomposed for the tube section upstream and downstream of the acoustic material. Subsequently, the pressure, P , and the velocity, V , of the wave at location m and n can be determined from the decomposition and they are related by

$$\begin{bmatrix} P \\ V \end{bmatrix}_m = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P \\ V \end{bmatrix}_n \quad (2-9)$$

where T_{11} , T_{12} , T_{21} , T_{22} are the coefficients of the Transfer Matrix. However, the Transfer Matrix could not be determined by Equation (2-9) alone, as there are 4 unknowns and only 2 equations. Nevertheless, the experiment could be repeated with another condition to give an additional set of P and V at location m and n , respectively.

Consequently, Equation (2-9) can be rewritten for two separate conditions denoted by the superscripts a and b to give the following:

$$\begin{bmatrix} p^a & p^b \\ V^a & V^b \end{bmatrix}_m = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} p^a & p^b \\ V^a & V^b \end{bmatrix}_n \quad (2-10)$$

As a result, there are 4 unknowns with 4 equations, thus the Transfer Matrix can be computed. To provide the two separate conditions as required by Equation (2-10), the sound source or the termination method could be changed. Due to this, the FMITM are sometimes referred to as the 2-load or the 2-source FMITM. For both variations, the criteria for the two conditions is they have to be as distinct to each other as possible. However, it is also recommended to use an anechoic termination to reduce the uncertainty of the measurement. Hence, for the 2-load FMITM, an anechoic termination is recommended for one of the conditions.

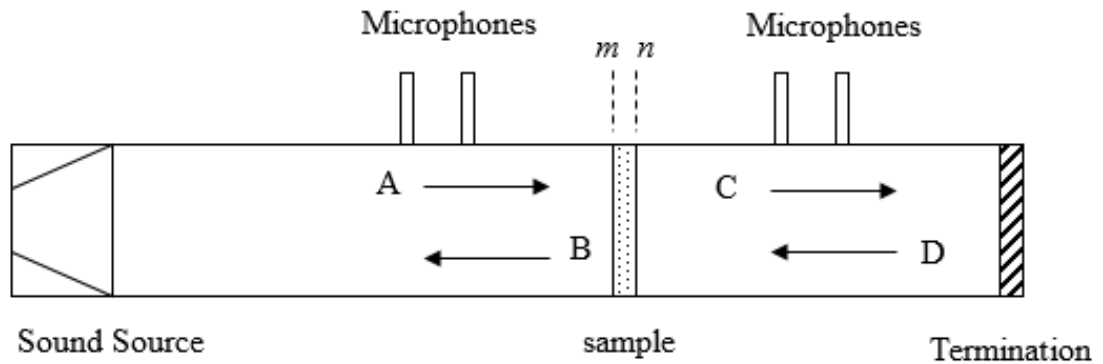


Figure 2.5: Illustration of the Four Microphone Impedance Tube Method. The upper-case letters (A, B, C, D) denotes the amplitude of the wave component.

After determining the Transfer Matrix, the Reflection Coefficient and Transmission Coefficient for the case where an anechoic termination is present ($D = 0$) is given as:

$$T_a = \frac{2 e^{ikd}}{T_{11} + \left(\frac{T_{12}}{\rho_o c}\right) + \rho_o c T_{21} + T_{22}} \quad (2-11)$$

$$R_a = \frac{T_{11} + \left(\frac{T_{12}}{\rho_o c}\right) - \rho_o c T_{21} - T_{22}}{T_{11} + \left(\frac{T_{12}}{\rho_o c}\right) + \rho_o c T_{21} + T_{22}}$$

where the subscript a denotes the anechoic termination and d is the thickness of the acoustic material (distance from point m to n).

Furthermore, if the V at location n in Equation (2-9) is equals to zero, as if a hard wall is present at that location, then the Reflection Coefficient is given as:

$$R_H = \frac{T_{11} - \rho_o c T_{21}}{T_{11} + \rho_o c T_{21}} \quad (2-12)$$

where the subscript H denotes the Hard Wall case.

2.2.3 Summary on Experimental Analysis of TAEs

The types of experimental analysis of TAEs were reviewed. Based on the review, the analysis procedures suitable to characterize the performance of the DEMO 2 Engine were determined, albeit some modifications were needed. For the acoustic power output measurement, the two-microphone method is the most suitable as its set up could also be used with the MMWDM. The MMWDM was selected to decompose the

soundwave produced by the DEMO 2 Engine as it is more accurate than the TMWDM. Therefore, both the two-microphone method for acoustic power measurement and MMWDM could be used simultaneously. Furthermore, the components in the DEMO 2 Engine could be treated as acoustic materials so that their acoustic properties could be determined by obtaining their Transfer Matrix.

On the other hand, due to the DEMO 2 Engine performance is still weak in comparison with TAEs published elsewhere, it is not of main interest to obtain the final efficiency of the DEMO 2 Engine for comparison with other TAEs [14], [27], [77]. Instead, it is more useful to first identify and characterize the main losses in the DEMO 2 Engine. In view of that, constructing a power flow chart for the DEMO 2 Engine is required to identify the heat losses throughout the components of the DEMO 2 Engine.

2.3 Numerical Modelling of TAEs

Early designs of TAEs rely heavily on the LTAT to accurately predict the operating conditions of the TAE. However, as the performance of TAEs continue to improve, researchers have found that the non-linear effects in the TAEs could not be neglected. While various approaches to construct numerical models of thermoacoustic systems have been developed, there is still a gap in the understanding of the phenomena happening in a thermoacoustic system. Despite that, to further analyze the characteristics of the DEMO 2 Engine, a numerical model to represent the DEMO 2

Engine is needed. In addition, a numerical model could also reduce the number of experiments needed to analyze the DEMO 2 Engine. The types of approaches in numerical modelling of TAEs is reviewed in this section and the most suitable approach to construct a numerical model of the DEMO 2 Engine is stated.

2.3.1 Linear Thermoacoustic Theory (LTAT)

The LTAT was established by Rott in his attempt to describe the “Taconis Oscillations” [78]. When one end of a tube is submerged in liquid helium and the other end left at room temperature, a sound wave is generated [5]. Rott approximated the interactions between the pressure, velocity and temperature of the air inside the tube from the first order heat equation, momentum equation and continuity equation, shown in equations (2-13), (2-14), and (2-15), respectively.

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2} \quad (2-13)$$

$$F = m \frac{du}{dt} \quad (2-14)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (2-15)$$

where F is the force and u is the x component of velocity.

Although Rott's approximation was intended for the interactions inside a tube, it is also valid for small channels such as those in the stack of a TAE. By establishing the following assumptions, equations (2-16), (2-17), and (2-18) were derived [78]:

- The system is linear. Second order effects are neglected.
- The effects of temperature on the viscosity are neglected.
- The temperature variations along the walls are much smaller than the absolute temperature.
- The walls of the tube are fixed and rigid.
- Oscillating variables are harmonic and exist in a single frequency only.

$$T_1 = \frac{1}{\rho_m c_p} (1 - h_\kappa) p_1 \quad (2-16)$$

$$- \frac{1}{i\omega} \frac{dT_m}{dx} \frac{(1 - h_\kappa) - \sigma(1 - h_v)}{(1 - f_v)(1 - \sigma)} u_1$$

$$dp_1 = - \frac{i\omega p_m dx / A}{1 - f_v} U_1 \quad (2-17)$$

$$dU_1 = - \frac{i\omega A dx}{\gamma p_m} [1 + (\gamma - 1)f_\kappa] p_1 \quad (2-18)$$

$$+ \frac{(f_\kappa - f_v)}{(1 - f_v)(1 - \sigma)} \frac{dT_m}{dx} U_1$$

The subscripts 1 indicate first order equations. h_v and h_k denote viscous function and thermal function, respectively. On the other hand, f_v and f_k denote Rott's spatially averaged viscous function and spatially averaged thermal function, respectively. A represents the area and T_m represent the average mean temperature in the tube.

By combining equations (2-16), (2-17), and (2-18), the Rott's wave equation is obtained and shown in equation (2-19).

$$[1 + (\gamma - 1)f_k]p_1 + \frac{\gamma p_m}{\omega^2} \frac{d}{dx} \left(\frac{1 - f_v}{p_m} \frac{dp_1}{dx} \right) \quad (2-19)$$

$$- \frac{c^2}{\omega^2} \frac{f_k - f_v}{1 - \sigma} \frac{dT_m}{dx} \frac{dp_1}{dx} \frac{1}{T_m} = 0$$

where c is the speed of sound.

Rott's wave equation approximates the changes in pressure, velocity and temperature along the tube. The detailed descriptions of the derivations of the equations are presented in a series of papers by Rott. This work is now credited for establishing the LTAT. Based on the theory, Hofler invented a standing-wave thermoacoustic refrigerator, which proved that the approximation by Rott is quantitatively accurate [77]. Subsequently, Ward and Swift from the Los Alamos National Laboratory applied the LTAT to develop a simulation software for thermoacoustic systems called DELTA EC (Design Environment for Low-amplitude Thermoacoustic Energy Conversion) [27], [79].

2.3.2 DELTA EC

By applying the approach that formed the LTAT, the developers of DELTA EC used the momentum and continuity equation to derive the pressure and volume flow rate along a system:

$$\frac{dp_1}{dx} = \mathcal{F}_{momentum} \left(\begin{array}{c} p_1, U_1, T_m, \rho_m, \omega, \text{geometry, gas properties,} \\ \text{solid properties, etc} \end{array} \right) \quad (2-20)$$

$$\frac{dU_1}{dx} = \mathcal{F}_{continuity} \left(\begin{array}{c} p_1, U_1, T_m, \rho_m, \omega, \text{geometry, gas properties,} \\ \text{solid properties, etc} \end{array} \right) \quad (2-21)$$

in which $\mathcal{F}_{momentum}$ is the momentum function and $\mathcal{F}_{continuity}$ is the continuity function.

Equations (2-20) and (2-21) are formed for a list of geometries widely used in thermoacoustic systems (such as compliance, duct, etc) [79], [80]. Users can then select and connect the appropriate geometries to represent a thermoacoustic system. Users are required to input the pressure, pressure phase, velocity and velocity phase at the beginning of the model and DELTA EC will integrate equations (2-20 and (2-21 along the axial position coordinate, x , to obtain the pressure, pressure phase, velocity and

velocity phase of the system. Figure 2.6 shows an example of a thermoacoustic refrigerator and its DELTA EC model.

In practical use of DELTA EC, it is common that users do not know all the information at the beginning segment but instead knows the boundary conditions at the end (e.g. $U = 0 \text{ m}^3/\text{s}$ at the wall). DELTA EC has a useful “Guess and Target” feature where users can input information at the end of the model as a target and DELTA EC guesses the missing information at the beginning of the model. DELTA EC varies the guesses until the integration results converge to the targets using an algorithm called DNSQ. The model of the Hofler’s refrigerator shown in Figure 2.6 was constructed to demonstrate the accuracy of DELTA EC. The output of the model was compared with data from Hofler’s thesis and good agreement was shown.

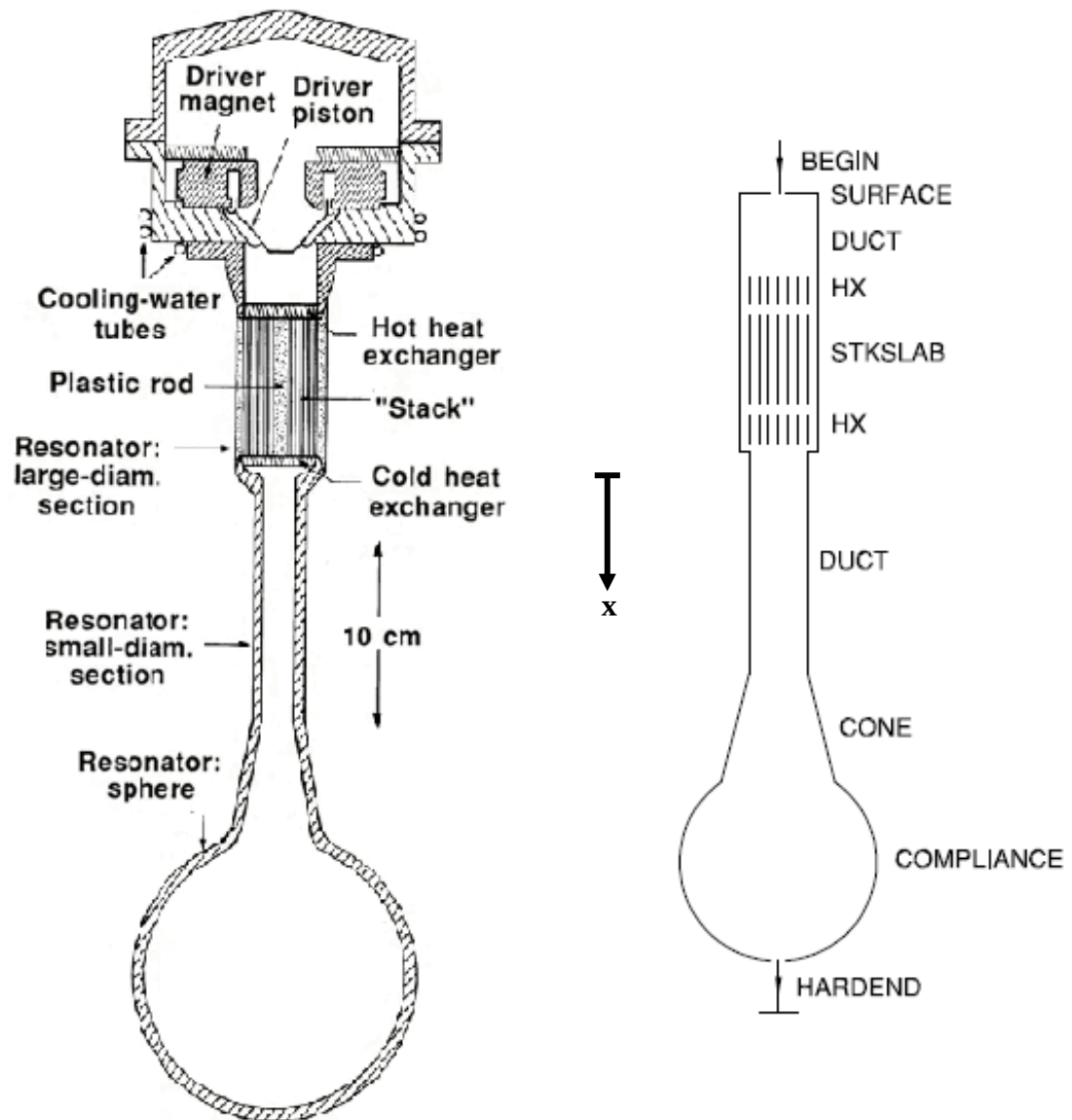


Figure 2.6: (a) Schematic diagram of the Hofler's thermoacoustic refrigerator.

(b) DELTA EC model of the Hofler's thermoacoustic refrigerator. [79]

DELTA EC is widely used for simulating low amplitude thermoacoustic systems. Yu et al. [32] used DELTA EC in designing a TAE with a linear alternator to convert sound wave to electricity. DELTA EC determined the performance of the TAE if the length of the feedback pipes of the TAE were altered. This enabled Yu et. al. [32] to decide the optimum length of the feedback pipe to facilitate the performance of its linear alternator. Kang et. al. [81] developed a thermoacoustic cooler driven by a cascade TAE. The interactions between the cascade TAE was simulated by DELTA EC. Li et. al. [82] also simulated a 3 stage TAE using DELTA EC. By applying the appropriate boundary conditions, only 1 stage was needed to be simulated by DELTA EC as all 3 stages were assumed to be identical.

Although DELTA EC has demonstrated adequate accuracy in simulating thermoacoustic systems, it is however limited to low amplitude systems only, as suggested by its name. This is due to the limitations of the LTAT, where second order effects were neglected. As the thermoacoustic field continues to develop, building higher amplitude systems became increasingly feasible and beneficial to continue exploiting the advantages of the thermoacoustic technology. For higher amplitude systems, the approximation by the LTAT is less accurate as the system becomes nonlinear.

2.3.3 Nonlinearity in Thermoacoustics

Rott's approximation that established the LTAT was initially intended to describe the phenomenon inside a circular tube. Arnott, Bass and Raspet expanded Rott's approximation to model the thermoacoustic effect in stacks with arbitrary pore geometries [83]. Arnott et. al included second order energy flux in the model and presented a range of conditions where Rott's approximation is accurate. Penelet et. al. [84] studied on the temperature distribution inside a stack and concluded that the nonlinearity between the acoustic and temperature fields affects the performance of the stack. The nonlinearity rises from acoustic streaming inside the system [85].

The most dominant types of streaming in thermoacoustic systems are the Rayleigh Streaming, Gedeon Streaming and Jet Driven Streaming. Rayleigh Streaming rises from the viscous stresses between the gas flow and the solid walls. Gedeon Streaming is described as the net gas flow in the system and it is due to the positive and negative directions of the gas oscillation do not cancel each other out completely. Gedeon Streaming is always present when there is a travelling wave [86]. Jet Driven Streaming occurs when sound wave propagates through an orifice or change in cross section. The flow pattern of a gas or viscous fluid exiting an orifice is different than when entering, as shown in Figure 2.7. Thus, the oscillating flow at the orifice causes the Jet Driven Streaming.

All these non-linear effects are often unavoidable in a TAE design, as these effects take place due to the geometry of the TAE and regardless of its operating frequency. Therefore, a well-designed TAE would have suppressed the effects from these non-linearities.

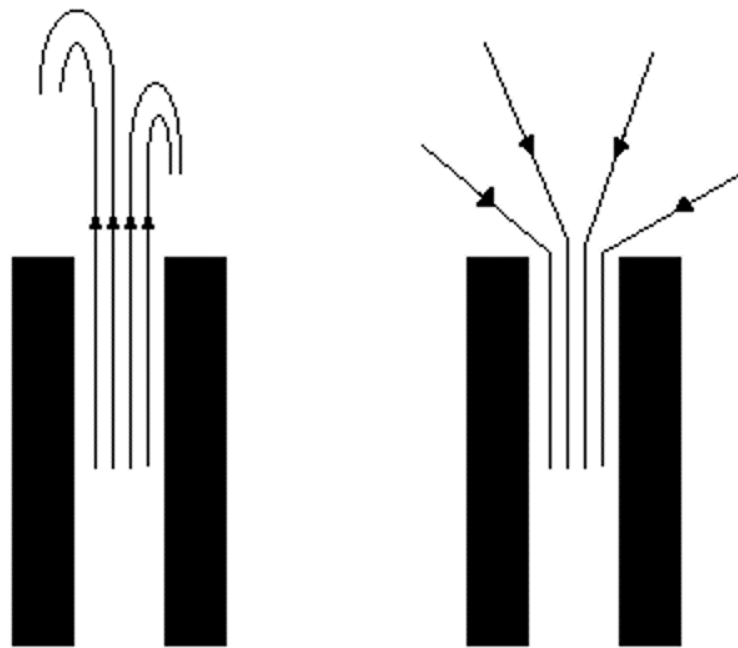


Figure 2.7: Flow pattern of fluid exiting and entering an orifice.

2.3.4 Computational Fluid Dynamics (CFD)

Lycklama, Tijani and Spoelstra have demonstrated the feasibility of using a commercial CFD software, ANSYS to simulate thermoacoustic systems [87]. The CFD model used was a simplified travelling wave TAE. The main focus of the model is to visualize the wave propagating through the parts of a TAE, thus the temperature of the heat exchanger walls was ignored in the model. Nonlinear effects such as Gedeon

Streaming and Jet Driven Streaming were successfully visualized at high pressure amplitude, confirming previous claims that nonlinear effects in thermoacoustic systems cannot be ignored.

However, Lycklama et. al. work was not compared to experimental results as it is intended as a demonstration of CFD capabilities in simulating thermoacoustic systems. Yu et. al. from the Chinese Academy of Sciences used the commercial CFD code, FLUENT 6.1 [88] to model a travelling wave TAE and its results were compared with experimental data [89]. Three comparisons were made:

- Onset temperature versus mean pressure in the TAE.
- The pressure amplitudes at four locations along the TAE.
- The pressure amplitudes versus the HHX temperature.

In all three comparisons, the CFD model showed good qualitative comparison. However, it predicted a better performance by the TAE. Nonlinear effects were visualized by the model as well. Yu et. al. agrees that CFD simulation is feasible in simulating thermoacoustic systems but a 3D CFD model is needed for a more accurate model. Scalo, Lele and Hesselink were the first to perform 3D modelling of a TAE [90]. Scalo et. al. adopted the simplified model used by Lycklama et. al. and extended it to 3D setup. The temperatures of the heat exchangers wall that were previously ignored were modelled based on empirical data available in literature. The model was able to

predict thermoacoustic effects that are expected in a TAE, however, since it is based on the simplified model of Lycklama et. al., the model was not compared to experimental data. Also, direct comparison between the visualization by the CFD model to experiment results is very difficult as measuring streaming experimentally is very challenging [20], [91]. Scalo et. al. [90] noted that high computational cost is required for the 3D modelling and proposed the usage of better grid refinement for the mesh and a simplified numerical model as a solution to the Navier-Stokes equation for modelling the acoustic streaming.

Sharify et al. [92] have also demonstrated the potential of using CFD to simulate the workings of a TAE. However, to save computational cost, the numerical model was only constructed for the region around the regenerator and experimental data were used as the input to the model at the boundary conditions. Kuzuu and Hasegawa [93] have showed that CFD could also predict the heat transfer behaviour in a Thermoacoustic Engine Core, but the scope of the work did not include comparisons with experimental data. Hariharan et al. [94] has used CFD to simulate the performance of a Standing Wave Thermoacoustic prime mover, but the model overpredicts the performances of the prime mover. Although CFD has shown promising results in constructing numerical model for TAE, at present, no CFD models have been able to predict all the output parameters of a TAE with good agreement and validation to experimental results.

2.3.5 Electrical Analogy

An alternative method to construct a numerical model for a thermoacoustic system is to describe the acoustic network by electrical analogy [95]–[99]. Sound waves behave similarly to electrical signals in an electric circuit. For instance, the potential difference between two points in an electric circuit encourages current to flow and the pressure difference between two points in an acoustic guide forces the air particles to propagate. It is obvious that the pressure and volumetric flow rate in acoustics is analogous to the voltage and current in electrical engineering respectively. The acoustic power is the product of the pressure and the velocity while the electrical power is the product of the voltage and the current. Based on this analogy, the impedance, compliance and inertance in acoustics is also analogous to the resistance, capacitance and inductance in electrical engineering respectively.

Using the electrical analogy, Riley has simulated a simple loop-tube TAE with using an electrical network analysis software called TINA [100]. Because the model was constructed from a wave point of view, the effects of the wave at many frequencies were showed as compared to CFD models which only describe the effect due to the fundamental frequency. By using suitable electrical components, the nonlinear effects could also be simulated. However, the quantitative comparisons with experimental results are not presented in the study.

De Blok and Van Den Brink [43] have also used an electrical analogy to analyze an acoustic network. De Blok applied the Scattering Matrix to describe the acoustic changes between two arbitrary planes in an acoustic guide. Figure 2.8 shows the graphical representation of the 2 ports Scattering Matrix. The arrows indicate the direction of the waves and the box indicates the part that is analyzed. The opposing direction of the arrows represents the reflection due to the arbitrary surfaces 1 and 2.

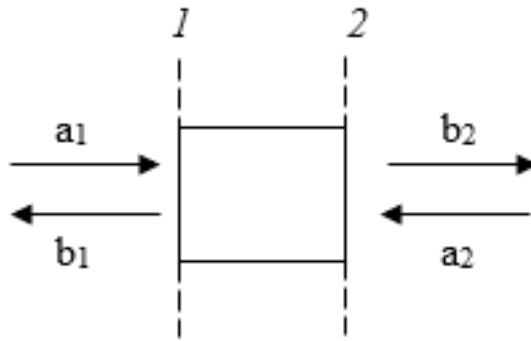


Figure 2.8: Graphical representation of the 2 ports Scattering Matrix.

Based on the graphical representation in Figure 2.8, the corresponding Scattering Matrix is:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad (2-22)$$

a and b are the forward and backward components of the soundwave, respectively. The subscripts 1 and 2 denote the respective location, as demonstrated in Figure 2.8. S_{11} is the reflection coefficient at 1, S_{12} is the reverse gain from 1 to 2, S_{21} is the forward gain

from 1 to 2, S_{22} is the reflection coefficient at 2. Then, the Standing Wave Ratio (SWR) entering 1 and exiting 2, denoted as SWR_{in} and SWR_{out} respectively, is given as:

$$SWR_{in} = \frac{1 + |S_{11}|}{1 - |S_{11}|} \quad (2-23)$$

$$SWR_{out} = \frac{1 + |S_{22}|}{1 - |S_{22}|} \quad (2-24)$$

By measuring the SWR inside the acoustic guide using a movable microphone, De Blok could characterize every component in the acoustic network as a black box. This is performed by monitoring the change of SWR at upstream and downstream of the component in the acoustic network. Therefore, with careful considerations in choosing the right electrical analogy, a thermoacoustic system can be represented by an electrical circuit.

2.3.6 Summary on Numerical Modelling of TAEs

The types of approaches to construct a numerical model of a TAE were reviewed. Depending on the objectives of constructing the numerical model, the advantages of each approach could be exploited effectively. For the DEMO 2 Engine, the peak pressure of the soundwave produced is still low such that the effects of non-linearity are not dominant. It is noted that the effect of non-linearity is highly associated with the performance rating of the TAE, and its magnitude increases when the performance rating of the TAE is higher. Since the DEMO 2 Engine has a relatively low performance,

modelling approaches that do not consider the non-linear effects are sufficient for the numerical modelling work in this study. In view of that, DELTA EC is the most widely accepted software in the thermoacoustic field for numerical modelling of thermoacoustic systems. Although DELTA EC was initially written based on the LTAT, its developers has expanded the integration equations to consider some non-linear effects, where some degree of intuition on the TAE system is needed from the user. Therefore, by conducting experimental investigations on the DEMO 2 Engine, the experimental results could be used together with DELTA EC to construct a numerical model of the DEMO 2 Engine. As a result, the DELTA EC model of the DEMO 2 Engine could be used to complement the experimental results for a more comprehensive analysis.

2.4 Chapter conclusion

The experimental analysis methods and numerical modelling approaches were reviewed. Based on the reviewed presented in this chapter, it is deduced that modifications to the existing measurement techniques are required for the experimental investigation on the DEMO 2 Engine. This is because some rectifications to the DEMO 2 Engine are made beforehand and subsequently alter the experimental setup. Therefore, the proposed measurement techniques have to be modified to cater to the changes made. Furthermore, rectifications to the DEMO 2 Engine are necessary as several defects in the engine are spotted, such as leaking and joint failure issues. Details of the

rectification and modification work will be reported and discussed in the following chapter.

Besides that, DELTA EC was selected as the software to construct a numerical model for the DEMO 2 Engine as it meets the requirements for the modelling process. This will be presented in Chapter 7.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, an overview of the work flow of this project is presented. Due to this project inherited the DEMO 2 Engine from past work, preliminary experiments were conducted to develop a basic understanding on the DEMO 2 Engine behaviour and characteristics. The results of these experiments showed that the DEMO 2 Engine performance was significantly affected by various issues. Rectifications made to these issues were described in detail in this chapter. Then, further modifications were made to the DEMO 2 Engine to improve the experimental investigations. Furthermore, the types of measurement taken to analyse the DEMO 2 Engine performance were described as well as the uncertainties of these measurements. Lastly, the experimental analysis methods used in this project were described in this chapter.

3.2 Work Flow

To achieve the aim and objectives of this project, several stages of experimental investigation and numerical modelling of the DEMO 2 Engine are required. The outcomes of both work are needed to complement each other and to proceed to its respective next stage. An overview of the work flow of this project is illustrated in

Figure 3.1. The flow of the work is presented from left to right, and the experimental investigations were carried out concurrently with the numerical modelling.

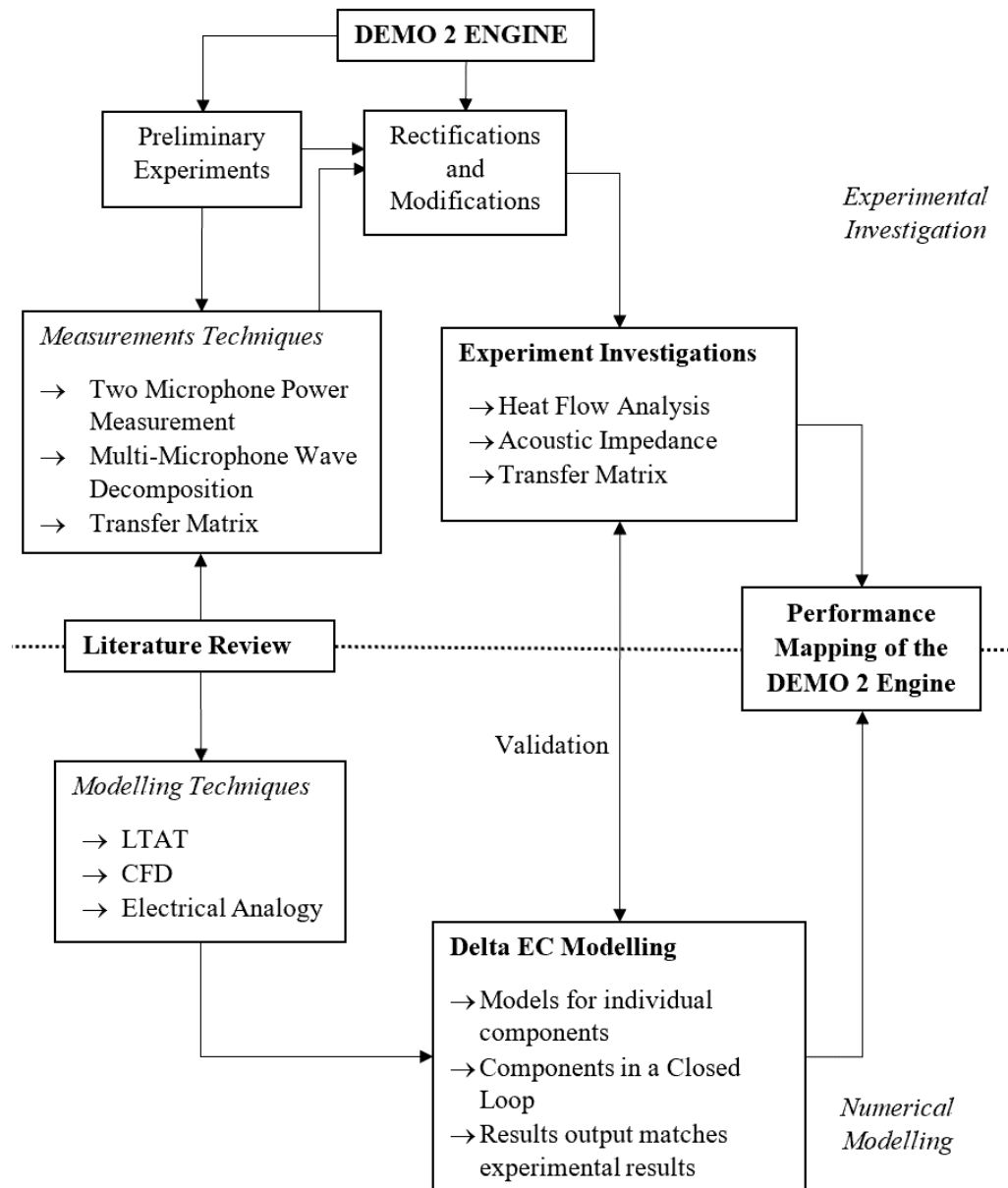


Figure 3.1: Work flow of the project.

The first stage of this project is to conduct preliminary experiments on the DEMO 2 Engine to develop a basic understanding as well as to familiarize with the operation of a thermoacoustic engine. In addition, from previous work on the DEMO 2 Engine, it was observed that the DEMO 2 Engine performance was very far below its design expectations. Therefore, the preliminary experiments were also used to identify problems affecting the DEMO 2 Engine performance.

Meanwhile, a literature review was carried out on experimental investigations and numerical modelling of thermoacoustic engines. The outcome of the review is to study the approaches and methods to experimentally evaluate a thermoacoustic engine and to construct numerical model of a thermoacoustic engine. These are discussed in CHAPTER 2. Based on the outcomes of the literature review and the preliminary experiment results, rectifications and modifications are subsequently made to the DEMO 2 Engine to improve further experimental investigations.

The experimental investigations on the DEMO 2 Engine is aimed at identifying and providing a quantitative evaluation of the main source of losses affecting the DEMO 2 Engine. The main form of energy transfer that are of interest in a thermoacoustic engine is from the heat source to the acoustic output. Hence, a heat flow analysis was carried out to investigate the sources of heat loss. Besides that, the frequency response of the DEMO 2 Engine was investigated to evaluate the acoustic losses in the DEMO 2 Engine.

In the meantime, a numerical model of the DEMO 2 Engine was constructed concurrently with the experiment investigations. DELTA EC was used to construct the numerical model as from the literature review it was concluded that this software is the most appropriate for this project. The objectives of constructing the DELTA EC model is to develop further understanding on the characteristics of the DEMO 2 Engine and identify behaviours of the DEMO 2 Engine that are unable to be observed through experimental investigations alone. The predictions of the DELTA EC model are validated against the experimental results.

Lastly, performance mapping of the DEMO 2 Engine is performed upon validation study. Here, it is important to highlight that the outcomes of both experimental investigations as well as numerical modelling are essential in order to accomplish the mapping exercise.

3.3 Rectifications made to the DEMO 2 Engine

Preliminary experiments on the DEMO 2 Engine shows that the peak pressure of the sound wave produced by the DEMO 2 Engine was only 1 kPa, which was very far below its expectations (i.e. 70 kPa). Upon investigation, it was found that the DEMO 2 Engine was leaking at various locations, causing the low sound pressure. Furthermore, the sealant between the HHX and the Lower Frame has failed due to it being subjected to high temperatures when the DEMO 2 Engine was operating at high heat input. In addition, the connection between the Feedback Loop to the TA Core also failed when

subjected to high pressure. Also, the Feedback Loop are made up of a series of PVC Pipes connected by collars and elbows. These connections at the collars and elbows also failed when subjected to high pressure. Besides the leaking of air pressure, it was noticed that the interface between the HHX and the TBV presents a significant reduction in cross sectional area for the acoustic wave path which will cause sound reflection and loss of sound energy to overcome the constriction. Rectifications made on these affected components are discussed in the following sections component by component.

3.3.1 Hot Heat Exchanger

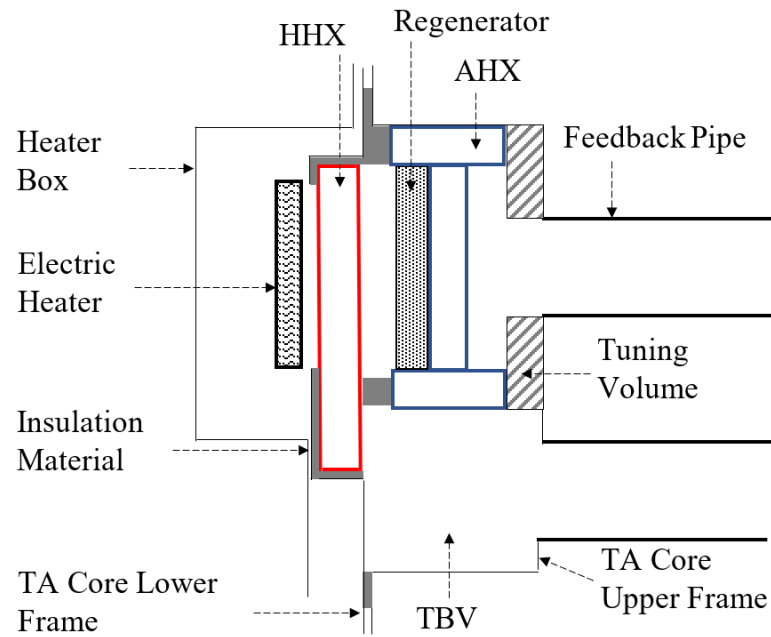
By observing the colour of the HHX while it was under heating as well as its burnt marks (See Figure A1 in Appendix A), the HHX is determined to be subjected to temperatures of approximately 700 °C during operation. It is noted that heating of stainless steel in air will cause discoloration at the heated surfaces. Hence, the temperature of the component can be determined based on the colour distribution of the heated surface and burnt marks, with the use of the heat tint colour chart [101]. The heat tint colours observed on the heated stainless-steel surface as well as the corresponding heating temperature are depicted in Table 3.1. Therefore, any sealing methods at the HHX must be able to withstand such high temperatures. Initially, the HHX was placed inside a Lower Frame and its sides were sealed by applying high temperature gasket. Unfortunately, it was found that the gasket has failed and thus air

from inside the TA Core is able to leak out. An obvious crack was found at the gasket sealing, as depicted in Figure A2 in Appendix A.

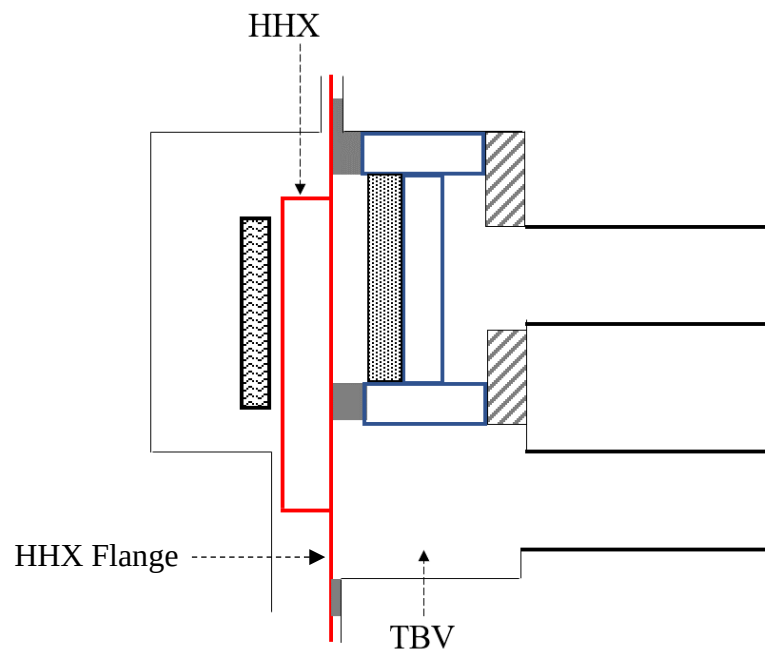
Table 3.1: Heat tint colours on the heated stainless-steel surface and the corresponding heating temperature [101].

Colour formed	Approx. temperature (°C)
Pale Yellow	290
Straw Yellow	340
Dark Yellow	370
Brown	390
Purple Brown	420
Dark Purple	450
Blue	540
Dark Blue	600

In view of that, the sides of the HHX was sealed by welding and a flange was welded to the HHX so that it could be bolted to the Upper Frame. The Lower Frame is then deemed to be unnecessary and it is removed altogether. The position of the heat transfer area of the HHX is also shifted towards the TBV to increase the cross-sectional area of the gap between the HHX and the TBV. Hence, the sealing of the HHX and the constriction between the HHX and the TBV were both rectified. A comparison of the HHX before and after these rectifications is illustrated in Figure 3.2. Further details of the rectification works performed on HHX and TBV can be obtained in Appendix A.



(a) Before



(b) After

Figure 3.2: Schematic diagram of the comparison between the HHX (a) before and (b) after rectification.

3.3.2 Feedback Loop

The Feedback Loop was initially connected to the TA Core after the TA Core was fully assembled. Due to this, the connection between the Feedback Loop and the TA Core was sealed by applying sealing putty at the outside surfaces of the connection, hence the sealing is weak. To overcome this, the TA Core was disassembled, and the sealing putty can be applied to the inner surface of the connections.

Besides that, because the Feedback Loop length was not optimized yet, the Feedback Loop is made up of straight pipes of various length and connected by PVC collars, instead of a long continuous pipe. Also, PVC elbows were needed for the Feedback Loop to form a closed loop. Usually, PVC solvents will be applied to the mating surfaces to connect the pipes to the collars or elbows. However, the collars and elbows cannot be sealed permanently to allow changes to the Feedback Loop length. The solution to this is to insert layers of thin plastic films to the mating surfaces to form a tight fit between the pipes and the collars or elbows. Then, PVC solvent was applied at the outer surfaces to seal the connections. When changes are required, alcohol or chloroform was used to remove the cured PVC solvent and the collar or elbow can be removed from the pipe by exerting adequate pulling force.

The next section describes further modifications to the DEMO 2 Engine to improve the experimental investigations.

3.4 Experimental Set Up Modifications

The DEMO 2 Engine was initially designed to be used on a wood burning cooking stove, but due to safety concerns and for a steady heat input, an electrical heater was used as the heat input to the DEMO 2 Engine. Two separate electrical heaters, each with a rated power output of 800 W, were placed in an insulated heater box that is connected to the frames of the TA Cores. Both heaters are separately controlled by a rheostat, so that the DEMO 2 Engine could be operated at various heat inputs. A power meter was also connected to the power supply of the electrical heaters to measure the electrical power drawn by the heaters.

Besides that, the DEMO 2 Engine initially only had two pressure sensors, one each to measure the pressure inside both of its TA Cores. However, due to the orientation of the DEMO 2 Engine, the pressure sensors are installed horizontally into the TA Core, which will cause inaccuracies in its measurements. In addition, simply knowing the pressure at one location does not provide significant information for further analysis to be carried out. Apart from that, there was only four thermocouples for each TA Cores to measure the temperatures of the hot side and cold side of the Regenerator as well as the AHX water inlet and outlet temperatures. These are also not sufficient to determine the power flow across the DEMO 2 Engine. Therefore, to provide a more comprehensive analysis on the performance of the DEMO 2 Engine, more pressure sensors and thermocouples were installed at specific locations within the TA Cores as well as in the Feedback Loop.

Hence, up to 16 pressure sensors was added to the Feedback Loop. These pressure sensors are flush mounted to 8 pieces of 30 cm PVC pipe sections to form 8 pairs of pressure sensors with a separation distance of 15 cm, as shown in Figure 3.3.



Figure 3.3: The Pressure Sensor pairings flush mounted to PVC pipe sections.

For all the pressure sensor pairs shown in Figure 3.3, the ends of the pipe section were connected to PVC collars to allow the entire section to be fitted into the Feedback Loop. These sensors are installed in pairs to facilitate the Wave Decomposition technique used, which will be discussed in Section 3.6.2. The locations of these pressure sensors vary according to the DEMO 2 Engine's configuration. The pressure sensor mounting was tested to be able to withstand the expected operating conditions, as shown in Appendix B.

In addition, a total of 40 thermocouples were installed at various locations in the DEMO 2 Engine. A K-type thermocouple was installed at every surface of the Heater Box and Upper Frame by keeping it in constant contact to its respective surface to measure the surface temperature. This will allow estimation of the heat loss from the Heater Box and the Upper Frame of the DEMO 2 Engine to be determined, as discussed in CHAPTER 5. Besides that, K-type thermocouples are also added in the Feedback Loop to determine the heat flow into the Feedback Loop. An illustration of the positions of the Thermocouples is shown in Figure 3.4.

All the pressure sensors and thermocouples are connected to its respective data acquisition device to convert the measured signal into digital signal, such that the recordings could be saved into a text (*.txt) file. The Pressure sensors are connected to the National Instrument 9237 Modules via a RJ50 cable. The K-types thermocouples inside the closed loop are wired to the National Instruments 9211 Modules. Both of these modules are connected to a National Instrument cDAQ 9888, which is subsequently connected to a personal computer via a USB connection. Apart from these, the T-type thermocouples measuring the AHX water inlet and outlet temperatures as well as the K-type thermocouples measuring the surface temperatures of the Heater Box and Lower Frame are connected to a PICO TC-08 Thermocouple Data Logger that is also subsequently connected to the personal computer via a USB connection. The entire experimental set up is illustrated in Figure 3.5. All the experimental data was recorded by a personal computer simultaneously.

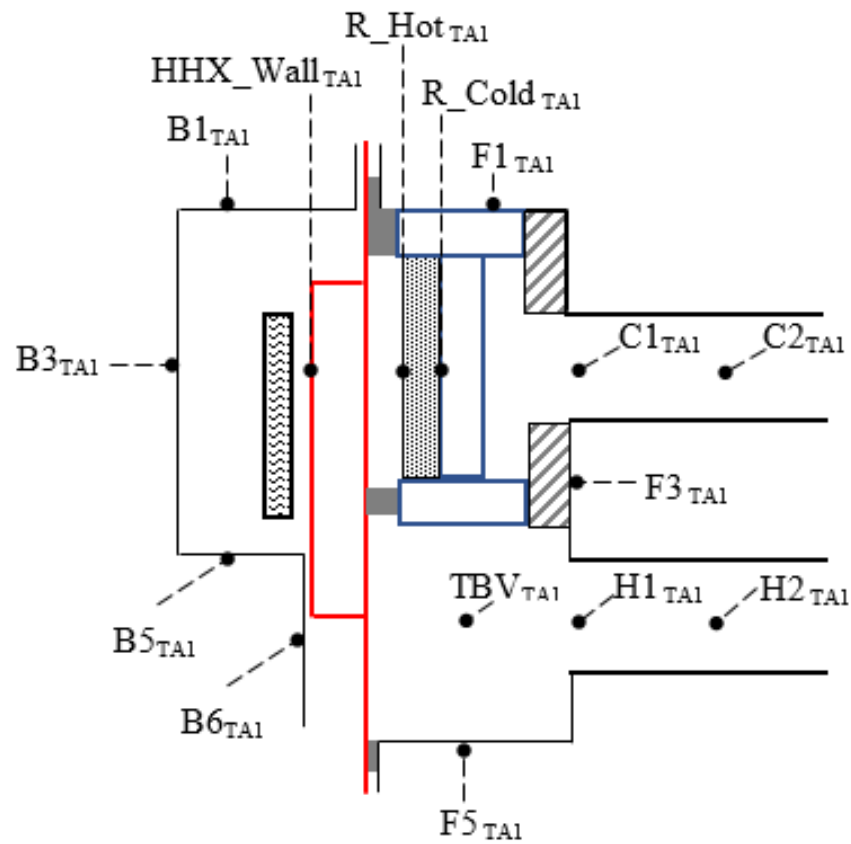


Figure 3.4: The positions of the thermocouples throughout TA Core 1 and the Feedback Pipe.

In the next section, the measurements taken during the experiments are discussed along with its respective uncertainties.

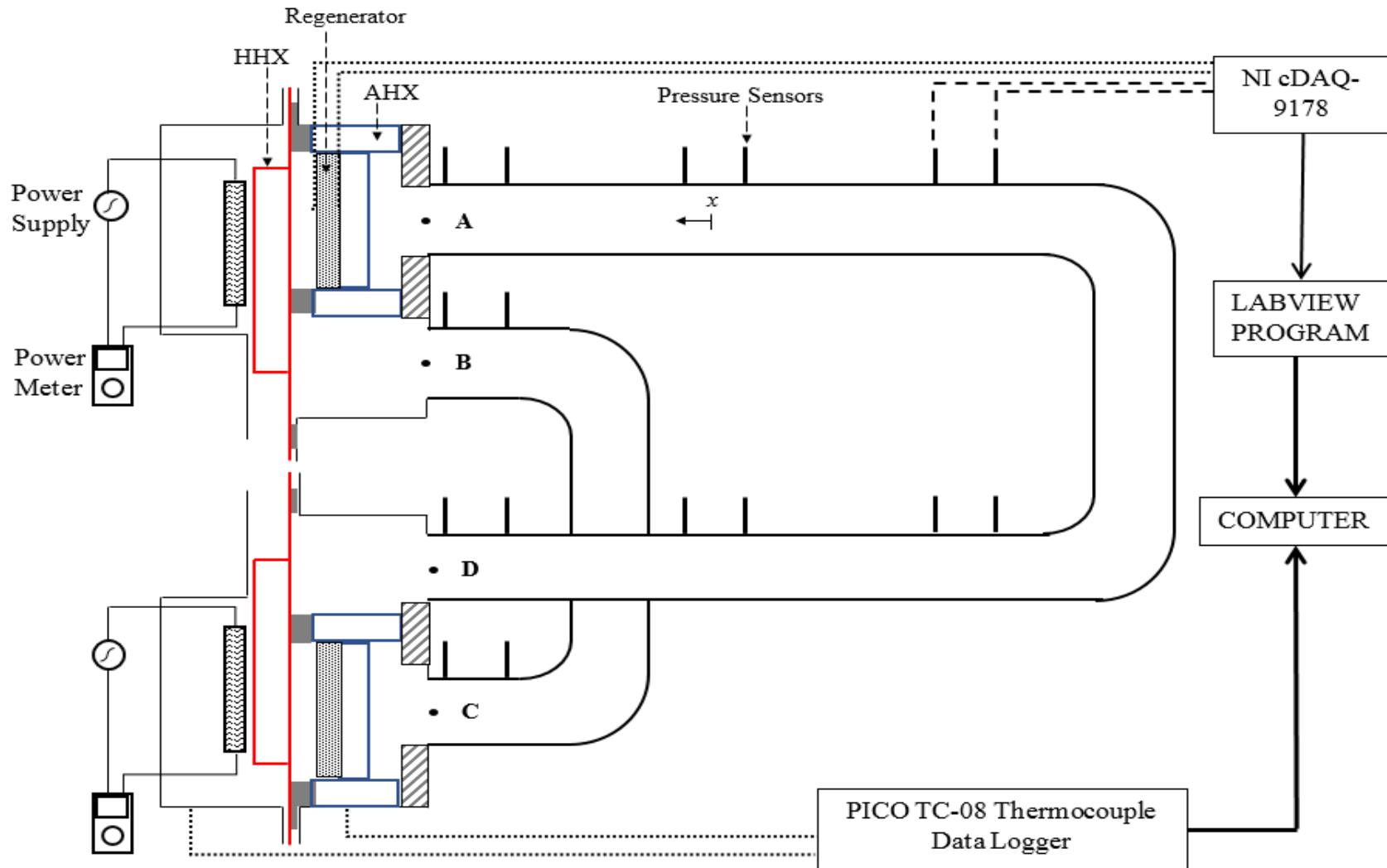


Figure 3.5: Schematic diagram of the DEMO 2 Engine experimental set up.

3.5 Measurements

As stated in the previous section, all the measurements taken during the experiments were converted to a digital signal and recorded simultaneously by a personal computer. Apart from that, measurements that could be taken directly through observation, such as length, flow rate, etc, were recorded as well. The following subsections discuss the types of measurements taken along with the method and equipment used.

3.5.1 Temperature

All the temperature measurements in the DEMO 2 Engine were taken using K-type thermocouples, except for the AHX water inlet and outlet temperatures, where a T-type thermocouple was used instead. The uncertainties of the K-type and T-type thermocouples are ± 2 K and ± 1.2 K respectively. The choice of using K-type thermocouples is because it can withstand temperatures as high as 800°C , whereas T-type thermocouples were used for the AHX water inlet and outlet temperatures because of its smaller uncertainty range and the measured water temperature is not expected to exceed the limit of the T-type thermocouples, which is at 80°C .

In addition, as stated in Section 3.4, two types of data acquisition devices were used for the thermocouples. For the thermocouples that were connected to the PICO TC-08 Thermocouple Data Logger, the samples are taken at a rate of 10 Hz. However, for the thermocouples that were connected to the National Instrument 9211 module, the sampling rate used is 1600 Hz. This is so that the sampling rate for these thermocouples

can be matched with that of the Pressure measurements, which will be discussed in the next subsection.

3.5.2 Pressure: Amplitude, phase and frequency

For measuring pressure, the pressure sensor used is the Impress Sensor IMP – Industrial Pressure Transmitter [102]. These sensors are a bridge-based sensor with four terminal outputs which are wired to a RJ50 cable to allow these sensors to be connected to the National Instrument 9237 Module [103]. The sampling rate used for these sensors are 1600 Hz.

To determine the pressure wave amplitude, phase and frequency, Fourier analysis was used [104]. The Welch's Averaging technique was performed on the recorded samples to obtain the Power Spectral Density (PSD) of the signal [68], [105]. Using the PSD, the amplitude and the frequency of the wave could be obtained. Besides that, the Fourier Transform of the pressure signal was determined to obtain the phase of the pressure.

3.5.3 Acoustic Power

Based on the literature review presented in Section 2.2, it is noted that the acoustic power measurement is useful in determining the useful work output produced by the heat engine, which is directly associated with the engine efficiency. It is concluded that the measurement is carried out using the two-microphone method, as its set up can be

used with the MMWDM which is employed to decompose the soundwave produced by the DEMO 2 Engine.

Every sensor pairing as shown in Figure 3.3 was used to determine the acoustic power at the midpoint of the sensors. The sensor separation distance is 15-cm. All the sensor pairings are mounted to the Feedback Loop as illustrated in Figure 3.5. The exact locations of the sensor pairings depend on the length of the Feedback Loop.

3.5.4 Electrical Heater Power Output

The electrical heater power output was measured using a Power Meter connected to the supply circuit of the electrical heater. The Power Meter displays the Voltage, Current and the Power passing through the electrical heater. The Power Output is the product of the Voltage and the Current.

Besides that, the Electrical Heaters are connected to the wall plug in the Laboratory for its power supply. Throughout the experiments, the power supply is steady and rarely fluctuates more than 1 W. Also, by referring to the Power Meter manufacturer data, the uncertainty of the Power Meter is ± 0.5 W. Hence, by taking the larger of the two, the uncertainty of the Electrical Heater Power Output measurement is ± 1 W.

3.5.5 Length

The dimensions of most of the components in the DEMO 2 Engine is important to be used in the experimental analysis as well as constructing the numerical model of the DEMO 2 Engine. A measuring tape was used to measure dimensions that are larger than 10 cm, such as the Feedback Pipes and heat exchangers. To measure dimensions that are between 1 to 10 cm, a ruler was used instead. For measuring pipe diameters, component thickness and any dimensions that are less than 1 cm, then a Vernier's calliper was used.

After taking all the necessary measurements before and during the experiments, the measured data are further analysed by the methods described in the preceding section.

3.6 Analysis Methods

The main objectives for the experimental investigations of the DEMO 2 Engine is to identify the losses that are affecting the DEMO 2 Engine performance. The two major losses in the DEMO 2 Engine is the heat loss and the acoustic loss. The analysis methods used to quantify these losses are described in the following subsections.

3.6.1 Heat Flow Analysis

To investigate the heat flowing through the DEMO 2 Engine, the assembly details of the entire DEMO 2 Engine was analysed to identify the heat flowing through every

individual component. As a result, the path of the heat flow throughout the DEMO 2 Engine was constructed as shown in Figure 3.6, and thus the heat flow in and heat flow out of every component was identified. Consequently, the design of the experiment analysis could be focussed on obtaining the values for every individual item shown in Figure 3.6.

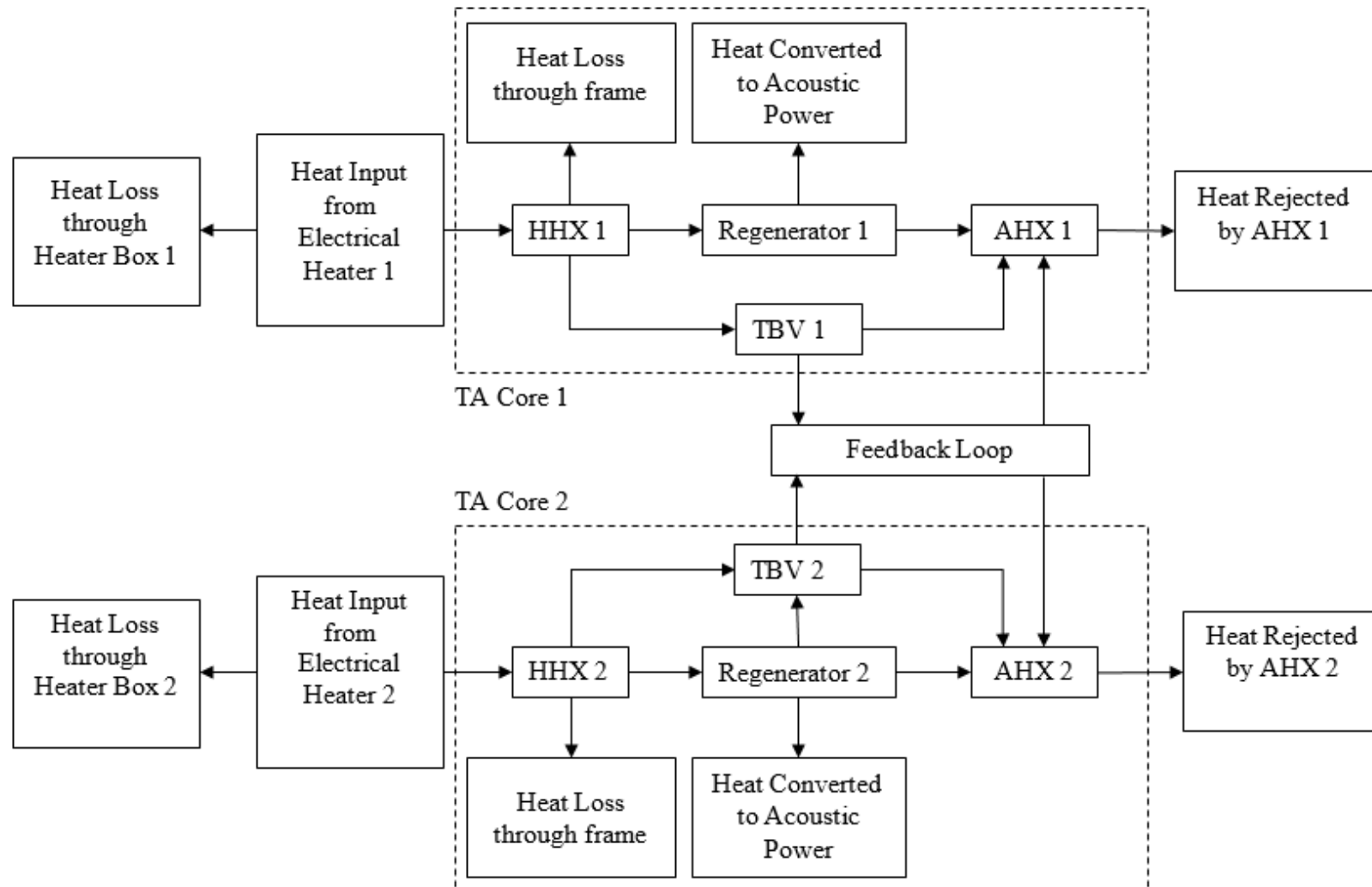


Figure 3.6: The heat flow network of the DEMO 2 Engine.

3.6.2 Wave Decomposition

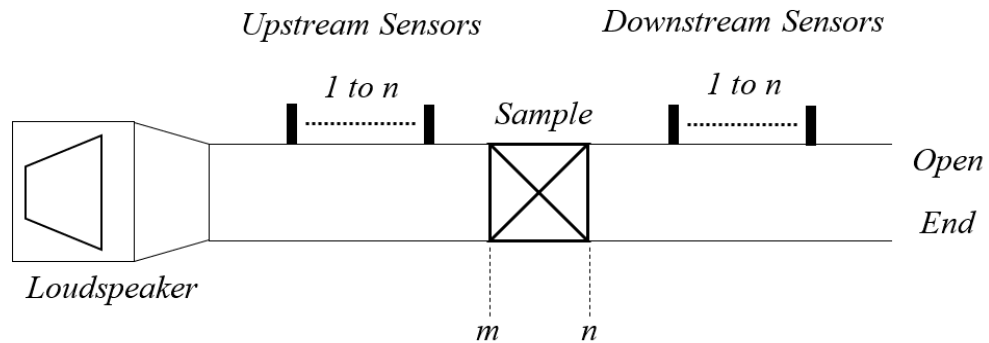
As summarized in Chapter 2, the MMWDM was used for all the experimental analysis that requires the wave decomposition. The approach utilizes every possible combination of a pair of microphones to perform wave decomposition and subsequently an average value is computed using the least square method [74] which aids to minimize the measurement uncertainties from a single pair of microphones, as discussed in Section 2.2. As illustrated in Figure 3.3, it is worth mentioning that the pressure sensors are mounted in pairs. Therefore, multiple pairs of pressure sensors were attached together in a straight line in this work to facilitate the use of the MMWDM. The number of pressure sensors and the distance between the pressure sensors sections used depends on the set up of every experiment. Besides that, due to the pressure sensors are already mounted to a PVC pipe section, the same type of PVC pipes was used as the waveguides for all the experiments conducted.

3.6.3 Transfer Matrix

Upon wave decomposition to its forward and backward components, further information such as the acoustic properties of the acoustic material can thus be further extracted with the use of a Transfer Matrix, as depicted in Section 2.2. As aforementioned, installation sensors at both the upstream and downstream locations of the sample is essential in order to determine the Transfer Matrix of the components in the DEMO 2 Engine. The approach used is called FMITM and its experiment set up is shown in Figure 2.5. It is noted that the FMITM was originally developed for the

2MWDM, as depicted in Section 2.2. However, it is revealed that the MMWDM is able to achieve greater accuracy level in soundwave decomposition as compared to the latter. Hence, the experiment set up of the existing FMITM was then expanded in this work to accommodate the MMWDM. This is illustrated in Figure 3.7. The number of pressure sensors used depends on the length of the waveguide. Apart from that, the 2-load method was provided by an Open End and a Closed End. Also, the sound source was provided by a Loudspeaker and a reducer was used to connect the Loudspeaker to the waveguide as the diameter of the Loudspeaker is larger than that of the waveguide.

Condition 1:



Condition 2:

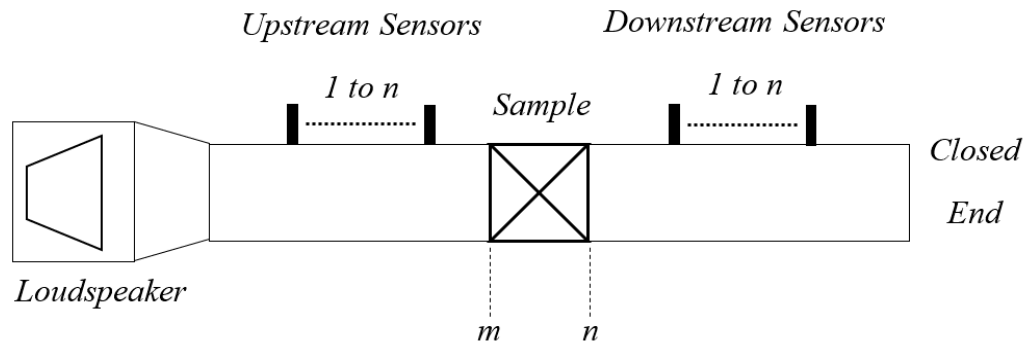


Figure 3.7: The 2-load Transfer Matrix method with the MMWDM.

3.7 Chapter Conclusion

The work flow of this project was described in this chapter. It is important to highlight that the experimental investigations were performed concurrently with the numerical modelling. The outcomes of both studies are essential to complement each other prior to the performance mapping of the DEMO 2 Engine. In addition, the flow of work presented in Figure 3.1 can also be applied to other two-stage travelling wave thermoacoustic heat engines that have similar performance rating.

In addition, the preliminary experiments conducted on the DEMO 2 Engine indicated that modifications to the DEMO 2 Engine was required, as summarized in Table 3.2. Besides that, the experimental analysis methods were also expanded for use on the DEMO 2 Engine and the summary is provided in Table 3.3.

Table 3.2: Summary of the rectifications/modifications made to the DEMO 2 Engine.

Component(s)	Engine Defect(s) / Issue(s)	Root Cause(s) / Contributing Factor(s)	Rectifications Done
HHX	Air leakage from internal of TA Core	Gasket failed under high temperature	<ul style="list-style-type: none"> • Welding of a flange to Upper frame of HHX • Lower Frame of HHX was removed • Reposition of heat transfer area of the HHX
Feedback Loop	Connection failure when subjected to high pressure	Weak sealing at the joint between Feedback Loop and TA Core	<ul style="list-style-type: none"> • Sealing putty was reapplied to the inner surface of the connections after TA Core was disassembled
		Connections between the pipes and collars/elbows cannot be sealed permanently to allow changes to the Feedback Loop length	<ul style="list-style-type: none"> • Insertion of layers of thin plastic films to mating surfaces to form a tight fit between the pipes and the collars/elbows • PVC solvent was applied to the outer surfaces to seal the connections so that it can be removed conveniently for modifications
Heater	Safety concerns and for steady heat input	Engine was originally designed to be used on a wood burning cooking stove	<ul style="list-style-type: none"> • Electric heater was used as the heat input to replace the cooking stove
Pressure sensors and thermocouples	Inaccuracies in pressure measurements	Pressure sensors were installed horizontally into the TA Core due to the orientation of the Engine	<ul style="list-style-type: none"> • Installed more pressure sensors and thermocouples at specific locations within the TA Cores and the Feedback Loop
	Insufficient information for further analysis of power flow	Only four thermocouples for each TA Cores were applied for temperature measurements	

Table 3.3: Summary of the experimental analysis methods used on the DEMO 2 Engine.

Analysis Method(s)	Description(s)
Heat flow analysis	<ul style="list-style-type: none"> • Assembly details of the entire DEMO 2 Engine was analysed • Heat flowing through every individual component was identified through the construction of a heat flow path
Wave decomposition	<ul style="list-style-type: none"> • Pairs of microphones were used to perform wave decomposition and an average value was computed using the least square method • MMWDM was applied throughout all the experimental analysis • Multiple pairs of pressure sensors were attached together in a straight line to facilitate the use of the MMWDM
Transfer matrix	<ul style="list-style-type: none"> • FMITM was applied to determine the Transfer Matrix • Sensors were installed at both the upstream and downstream locations of the sample • MMWDM was designated to perform soundwave decomposition in view of its higher accuracy level

CHAPTER 4

HEAT FLOW ANALYSIS

4.1 Introduction

When analysing thermoacoustic systems, much attention is usually focused on the acoustic field and perhaps more attention should also be given to the thermal analysis of the thermoacoustic system. For the DEMO 2 Engine, a qualitative representation of its heat flow network was described in the previous chapter. The benefits of having a heat flow network is that it provides an overview on the amount of heat flowing through the DEMO 2 Engine and thus further analysis can be focussed on estimating the heat power at every junction of the heat flow network. The analysis carried out to quantify the heat flow network is described in this chapter. The results of the heat flow analysis were also used in evaluating the acoustic performance and numerical modelling of the DEMO 2 Engine, as discussed in the other chapters.

4.2 Heat Flow Network

By observing the Heat Flow Network, shown in Figure 3.6, it is obvious that the two most straightforward measurements are the Heat Input from the Electrical Heaters and the Heat Rejected at the AHX. The Heat Input from the Electrical Heaters are measured

as described in Section 3.5.4. The Heat Rejected at the AHX, $\dot{Q}_{\text{rejected}}$ are assumed to be equal to the heat gained by the cooling water flowing through the AHX, so that

$$\dot{Q}_{\text{rejected}} = \dot{m}c_p(T_{\text{outlet}} - T_{\text{inlet}}) \quad (4-1)$$

where $\dot{m}$ is the mass flow rate of the cooling water, c_p is the specific heat capacity of water, T_{outlet} and T_{inlet} are the temperature of the water at the outlet and inlet of the AHX, respectively.

To populate the heat flow network shown in Figure 3.6, the DEMO 2 Engine was operated at various heat input and it was found that all the values are proportionate to the Heat Input from the Electrical Heaters. Figure 4.1 illustrates the amount of heat loss through the Heater Box and the remaining heat that are input into the HHX and from then on, the heat flow within the TA Cores and subsequently to the Feedback Loop.

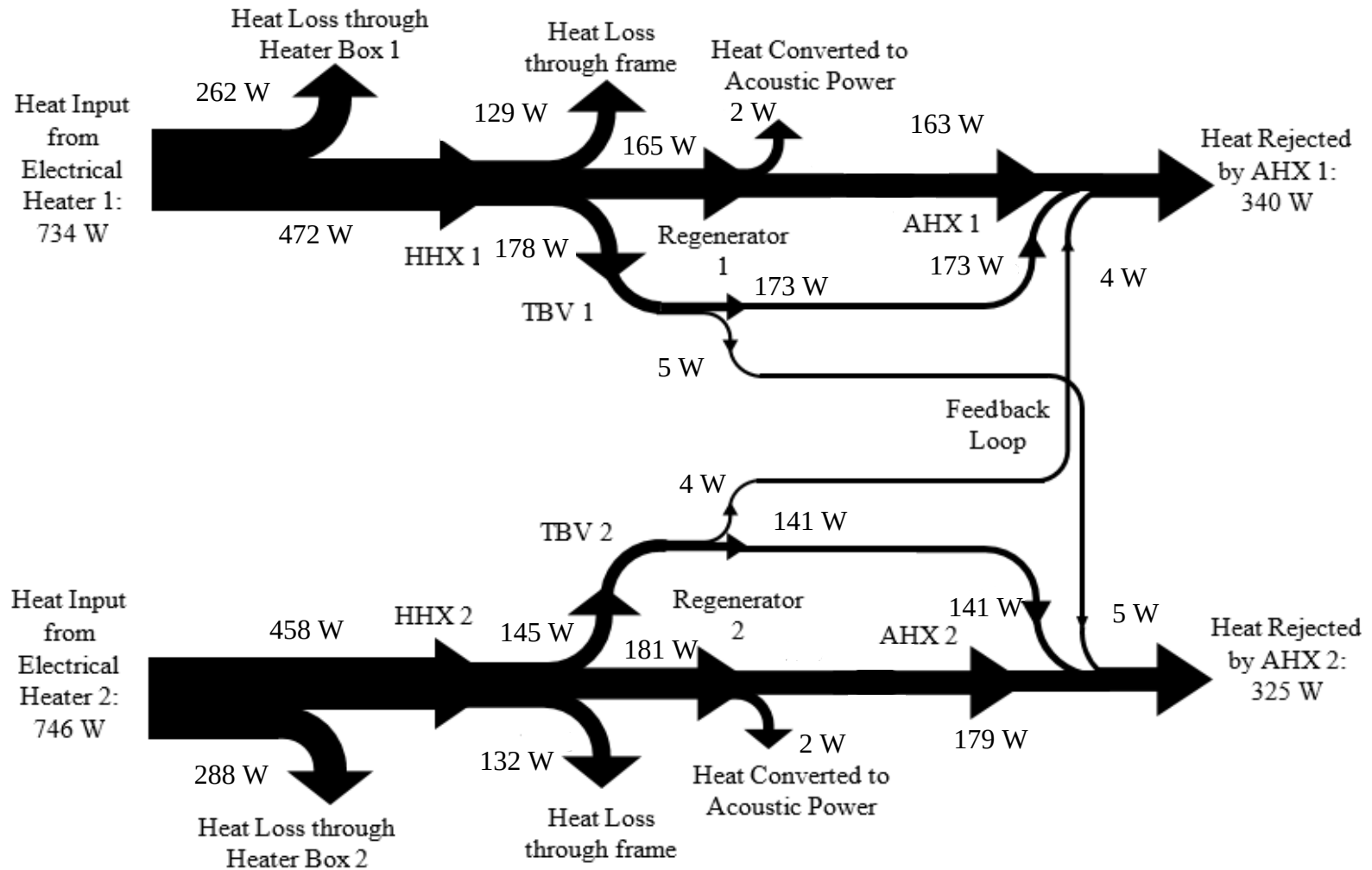


Figure 4.1: Heat flow chart of the DEMO 2 Engine.

Despite that, it is very challenging to obtain the heat flow through every individual component in the TA Core because there are limited thermocouples in the TA Core. Instead, the total heat losses within the TA Core were categorized as the parasitic heat losses [106]. Then, the parasitic heat losses could be determined experimentally, and subsequently the experiment results are used to construct the DELTA EC model, as discussed in CHAPTER 7. With the DELTA EC model, the heat flow through every individual component was determined and presented in Figure 4.1. Further details of the heat flow analysis were presented in Section 7.4 of CHAPTER 7.

The subsequent sections describe the experimental analysis carried out to determine the heat flow in the Heat Flow Network shown in Figure 4.1.

4.3 Heat Loss to Environment

One of the most frequently encountered problem in thermal engineering is the heat loss to environment. Due to the DEMO 2 Engine was intended for commercial use, it was designed to be as compact as possible. In addition to that, it was not initially intended to have an electrical heater. These has led to insufficient space for an insulated Heater Box to house the Electrical Heaters. Besides that, there is also insufficient volume in the TA Cores to insulate the heat exchangers from the frames of the TA Cores. Collectively, these has led to unavoidable heat losses to the environment.

To determine the heat loss to environment from the DEMO 2 Engine, all the surface temperatures of the Heater Box and the TA Core Upper Frame were measured using either K-type or T-type thermocouples. Details of these thermocouples can be found in Section 3.5.1. The objective of measuring the heat loss from the Heater Box is to determine the amount of heat that is input at the HHX, as illustrated in Figure 4.1. On the other hand, the objective of measuring the heat loss from the TA Core Upper Frame is to determine the parasitic heat losses through the TA Cores, which will be described in Section 4.5.

Due to limited resources, it was assumed that all the surface temperatures are uniform across its respective surface so that only one thermocouple is needed to measure each surface through direct contact. This assumption was justified during preliminary experiments whereby the temperatures of multiple locations across every surface were taken and results obtained indicate that the largest differences between the maximum and minimum temperature of a surface is not more than 6 °C. For the heater box frame, the temperatures of 9 equally-spaced location in a 3x3 mesh formation were taken for every surface. For the TA Core frames, the shape of the surfaces is in a more rectangular form, hence the temperatures of 3 equally-spaced locations in a 3x1 mesh formation were measured instead.

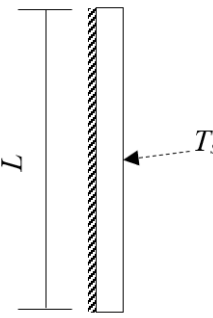
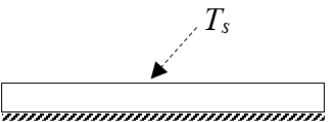
Furthermore, it also assumed that the heat losses are through natural convection and radiation from the surfaces. Therefore, the total heat loss from every surface is the sum

of the heat loss through natural convection and radiation from the respective surface. The formulations used to determine these two forms of heat losses are described in the following subsections.

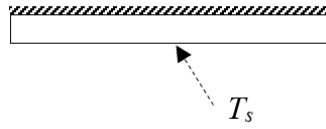
4.3.1 Heat Loss by Natural Convection

To determine the heat losses through natural convection, the surfaces of the Heater Box and Upper Frame were categorized into three types of geometries, as shown in Table 4.1.

Table 4.1: The empirical correlations of Nu for natural convection over various geometries.

Geometry	L_c	Nusselt Number, Nu
<p><i>Vertical Plate</i></p> 	L	$Nu = \left\{ 0.825 + \frac{0.387 Ra_L^{\frac{1}{2}}}{\left[1 + \left(\frac{0.492}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right\}^2$
<p><i>Horizontal Plate</i></p> <p>(a) Hot Upper Surface</p> 	$\frac{\text{Surface Area}}{\text{Perimeter}}$	$Nu = 0.54 Ra_L^{\frac{1}{4}}$

(b) Hot Lower Surface



$$\frac{\text{Surface Area}}{\text{Perimeter}}$$

$$Nu = 0.27 Ra_L^{\frac{1}{4}}$$

For every geometry, the average Nusselt number, Nu , was determined based on empirical correlations for natural convection and it is summarized in Table 4.1 [107]. To use the correlations in Table 4.1, the Rayleigh Number, Ra_L , for all the cases was determined using Equation (4-2).

$$Ra_L = Gr_L Pr = \frac{g\beta(T_{surface} - T_{ambient})L_c^3}{\nu^2} Pr \quad (4-2)$$

where g is the acceleration due to gravity, β is the thermal expansion coefficient, $T_{ambient}$ is the ambient temperature, $T_{surface}$ is the surface temperature, ν is the kinematic viscosity, L_c is the characteristic length and Pr is the Prandtl number.

All the air properties are evaluated at the film temperature, T_f , which is:

$$T_f = \frac{T_{surface} + T_{ambient}}{2} \quad (4-3)$$

Then, the heat transfer coefficient, h was determined using Equation (4-4).

$$Nu = \frac{hL_c}{k} \quad (4-4)$$

where k is the thermal conductivity and Nu is the Nusselt number. Subsequently, the rate of heat loss through natural convection was determined using:

$$\dot{Q}_{natural\ convection} = hA_s (T_{surface} - T_{ambient}) \quad (4-5)$$

In this study, heat loss by forced convection was not considered as there was no heat transferred across the system driven by an external source (e.g. fan).

4.3.2 Heat Loss by Radiation

Subsequently, the surface temperatures of the Heater Box and Upper Frame was also used to determine the heat loss through radiation. The heat loss through radiation for every surface was determined using

$$\dot{Q}_{radiation} = \epsilon A_s \sigma (T_{surface}^4 - T_{ambient}^4) \quad (4-6)$$

where ϵ is the emissivity of the material [108].

4.4 Heat Input at HHX

The HHX of the DEMO 2 Engine was designed to enable heat input from the flue gas of the cooking stove to the gas in the acoustic loop. Usually, the performance of a heat exchanger is rated according to its ability to transfer heat from one side to the other [108]. However, this would involve incorporating the DEMO 2 Engine on a cooking stove and is not the focus of this project. Therefore, the heat input at the HHX was determined by simply taking the difference between the Heat Input at the Electrical Heater and the Heat Loss by the Heater Box, as shown in Figure 4.1.

4.5 TA Cores Parasitic Heat Loss

To analyse the parasitic heat loss through the TA Core, an energy balance equation is written as below:

$$\dot{Q}_{in} = \dot{Q}_{rejected} + \dot{Q}_{parasitic\ loss} + \dot{Q}_{acoustic} \quad (4-7)$$

where $\dot{Q}_{in}$ is the heat input rate from the HHX, $\dot{Q}_{rejected}$ is the heat rejected rate at the AHX, $\dot{Q}_{parasitic\ loss}$ is the total rate of parasitic heat losses and $\dot{Q}_{acoustic}$ is the acoustic power generated by the TA Core [109]. $\dot{Q}_{parasitic\ loss}$ is the term used to represent all the heat losses from the TA Core. For an ideal TA Core, $\dot{Q}_{parasitic\ loss}$ is equals to zero and if the acoustic circuit of the TA system is opened to ensure no acoustic power generation will occur, then the last two terms of Equation (4-7) can be removed. Physically, this would mean that for an ideal TA Core, all the heat input is rejected when there is no acoustic work output and for the case when there is acoustic work output, the acoustic power generated is equalled to the difference between the heat input and heat rejected, as illustrated in Figure 4.2.

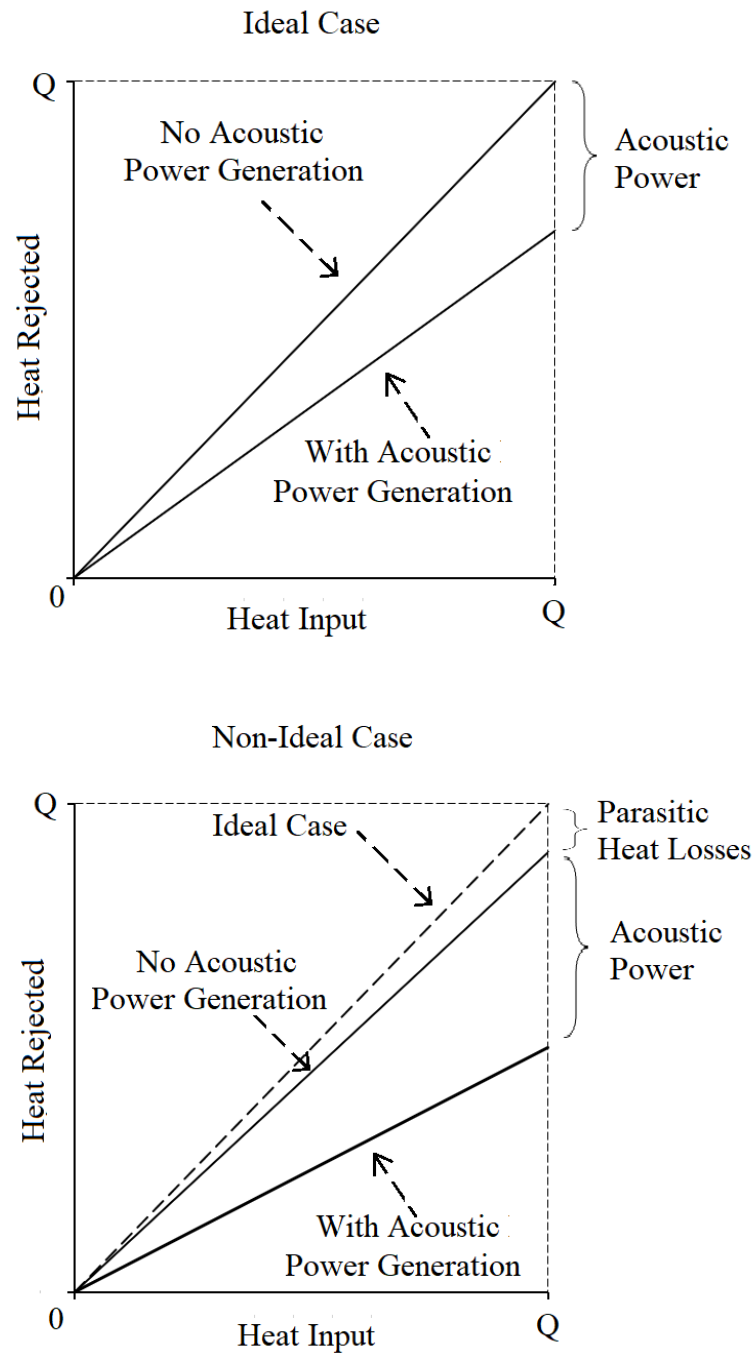


Figure 4.2: Illustration of the parasitic heat losses of a non-ideal TAE.

For a non-ideal TA Core, when the acoustic circuit is opened, the heat input equals the sum of heat rejected and parasitic heat loss. Therefore, the $\dot{Q}_{\text{parasitic loss}}$ of a TA Core can be determined by obtaining the difference between the heat input and heat rejected by the TA Core in an opened acoustic circuit [110].

Hence, for the DEMO 2 Engine, the Feedback Loop was removed to create an opened acoustic circuit and these open ends were insulated. Then, both TA Cores were subjected to various heat inputs and all the relevant temperatures were recorded when a steady state was achieved. Then, the heat input at HHX was determined by subtracting the Heater Box losses from the Electrical Heat Input. Apart from that, the heat rejected at the AHX was determined by Equation (4-1). Subsequently, the heat input at the HHX is plotted against the heat rejected at the AHX for various heat input to both TA Core 1 and TA Core 2, as shown in Figure 4.3.

By referring to Figure 4.2 and Figure 4.3, it can be deduced that there are large parasitic heat losses for both TA Cores. Apart from that, it is also observed that the parasitic heat losses in TA Core 1 is greater than that of TA Core 2. The difference is evident, as shown in Figure 4.3. Besides that, the acoustic power generated by both TA Cores are found to be very low, i.e. approximately 2 W.

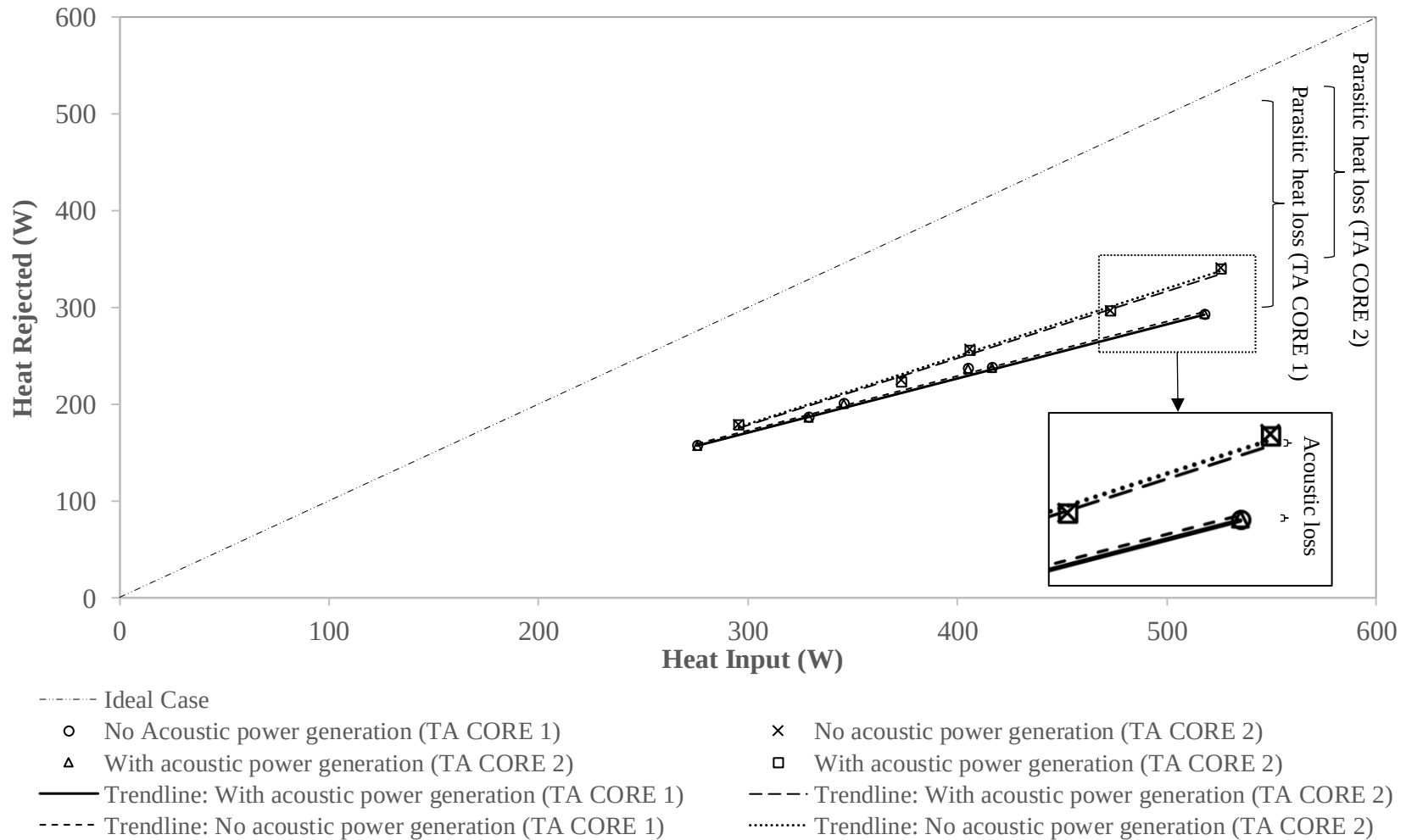


Figure 4.3: The parasitic heat losses of TA Core 1 and TA Core 2.

4.6 Chapter Conclusion

A heat flow network was constructed for the DEMO 2 Engine to show the heat flowing through every individual component in the DEMO 2 Engine. The heat flow network was constructed based on the results of the experimental investigations as well as the results output from the DELTA EC model. In addition to that, the parasitic heat losses within the TA Core was determined. Findings in Section 4.5 (see Figure 4.3) indicate that there is a significant amount of parasitic heat losses in both TA Cores and the acoustic power output of the DEMO 2 Engine is very low.

CHAPTER 5

EFFECTIVE LENGTH AND ACOUSTIC IMPEDANCE

5.1 Introduction

In analysis of acoustic systems, two key features that would affect the characteristics of an acoustic component is its effective length and acoustic impedance. The natural frequency of an acoustic system is dependent on the total length of the system, hence obtaining the length of every component is important to determine the natural frequency of the system. Unfortunately, accurately determining the length of some commonly used engineering components, such as heat exchangers, elbows, etc, proves to be a challenging task. Instead, it is much easier to determine an effective length to represent the component of interest. Besides that, every time a propagating soundwave encounters a change in cross-section area in its wave path, the impedance of the soundwave will change too. A mismatch in acoustic impedance would cause reflection of the soundwave. Again, it is difficult to keep the cross-section area of an entire system to be constant. Hence, for every component used in the DEMO 2 Engine, its effective length and the change in impedance was determined and discussed in this chapter.

5.2 TA Core Effective Length

The TA Cores of the DEMO 2 Engine were designed such that both TA Cores could absorb heat from the same side and the physical distance between them are kept to a minimum. These would allow freedom for the cooking stove to be designed separately as designing an integrated system comprising of the DEMO 2 Engine and the cooking stove will be a much more challenging task. In addition, the overall space taken by the DEMO 2 Engine is kept to a minimum as a bulky design is not feasible in actual application and would not be appealing to potential users. To accomplish these, one side of the HHX is exposed to an external heat source while the acoustic wave propagates at the other side. However, this imposes a design constrain on the TA Core in which the acoustic wave path will encounter a change in direction as it propagates through the TA Core. All of these contributes to a compact integration of the acoustic components within the TA Core, as shown in Figure 3.4. Consequently, it proves to be a challenge to measure the length of the wave path inside the TA Core.

The obvious method to determine the length of the wave path inside the TA Core is to simply add together all the dimensions of the components inside the TA Core that is parallel to the propagation direction of the wave. The dimensions of the components inside the TA Core could be obtained from its construction details or measuring them individually prior to the assembling of the TA Core. By doing this, the length of the wave path inside each TA Core is measured as 52 cm. However, this method did not consider the imperfect contact between every mating surfaces in the TA Core, which

will add to the overall length. Besides that, the complex geometries of the components in the TA Core will cause non-linear effects to occur, such as those discussed in CHAPTER 2. These non-linear effects could also alter the acoustic length of the components in the TA Core.

Instead, a method to obtain an effective length of the wave path inside the TA Core was proposed. Firstly, the DEMO 2 Engine was operated at various frequencies by changing the length of the Feedback Loop. For every frequency, the corresponding length of the Feedback Loop was measured. Then, the wavelength, λ , of the soundwave produced by the DEMO 2 Engine was determined by

$$\lambda = \frac{1}{f} c \quad (5-1)$$

where f is the frequency of the soundwave and c is the speed of sound at room temperature of 28 °C, which is taken as 346 m/s. Then, the wavelength is compared with the measured feedback loop length, as shown in Figure 5.1. It was observed that there is a constant 110 cm difference between the wavelength and the measured feedback loop length. Therefore, by ignoring manufacturing tolerances, the effective length of each TA Core equals to 110 cm divided by 2, which is 55 cm.

The importance of obtaining the effective length of the TA Core is to determine the optimum feedback loop configuration, which will be discussed in the next section.

Apart from that, this effective length was also used in the numerical modelling of the DEMO 2 Engine, which will be discussed in CHAPTER 7.

Feedback Loop Length Offset

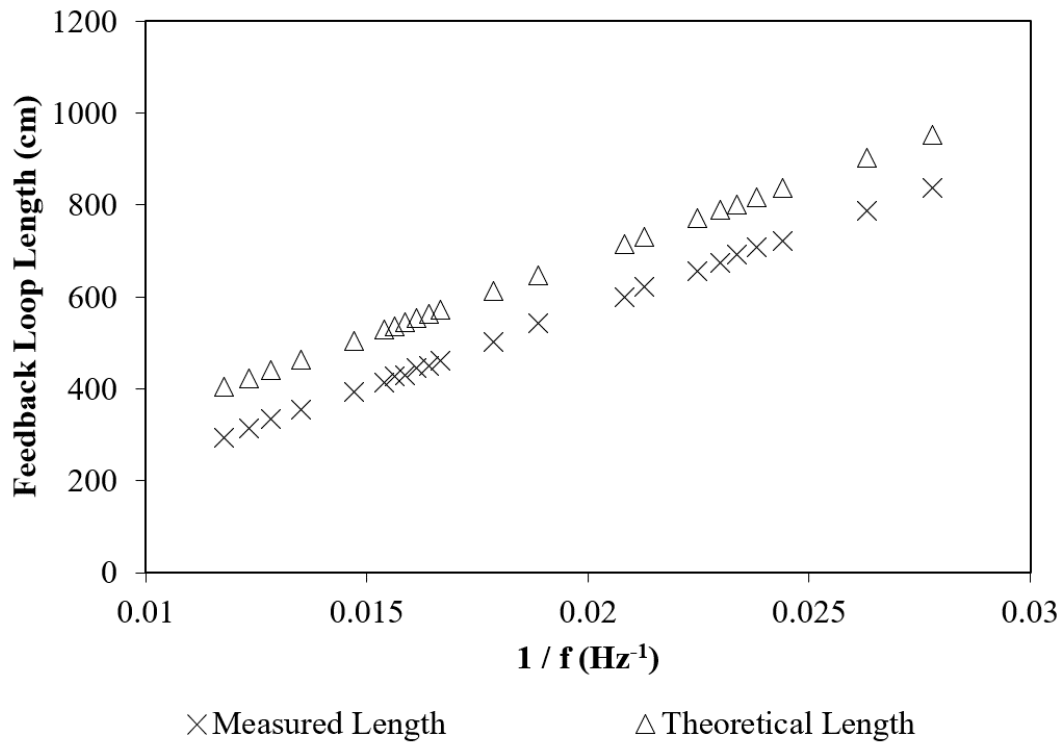


Figure 5.1: The wavelength and measured feedback loop length at various frequencies.

5.3 Optimum Feedback Loop Configuration

Before discussing on the feedback loop configuration, it is essential to keep in mind that the soundwave produced by the DEMO 2 Engine will be converted to electrical

energy. The initial proposed method to convert the acoustic energy to electrical energy is by using a low cost Linear Alternator, and for most Linear Alternator, there is bound to be an optimum operating frequency range where it could perform the conversion at its highest efficiency. Therefore, in the design methodology of the DEMO 2 Engine, an operating frequency was selected based on a Linear Alternator and then the DEMO 2 Engine was designed to have an optimum operating frequency that matches with the Linear Alternator operating frequency. Consequently, the Feedback Loop length was determined based on this optimum frequency and by using Equation (5-1).

Set against this background, another important feature of the DEMO 2 Engine to be highlighted is its impedance self-matching capabilities. The feedback loop was initially configured such that the TA Cores were separated by a quarter-wave tube. This is so that the impedance of a TA Core will be matched with the other TA Core, similar to how a quarter wave transformer matches the impedance of a transmission line to a load, and thus eliminating soundwave reflection as it travels from one TA Core to the other. Referring to Figure 3.5, the initial configuration of the feedback loop was such that the distance from point B to point C was made to equal a quarter of the wavelength of the soundwave produced by the DEMO 2 Engine. Other than that, the distance from point D to point A is made to equal 3 quarter of the wavelength of the soundwave. A feedback loop ratio was defined as the ratio of the length BC to length DA. Based on this, the desired feedback loop ratio is 3:1 such that the section BC is a quarter of the wavelength of the soundwave. However, this procedure neglects the length contributed by the

components in the TA Core. To rectify this procedure, the feedback loop ratio was redefined as

$$\text{Feedback Loop Ratio} = \frac{0.55m + \text{Length } DA}{0.55m + \text{Length } BC} \quad (5-2)$$

where 0.55 m is the effective length of the TA Core as determined in Section 5.2. To obtain the optimum feedback loop configuration, the DEMO 2 Engine was operated at various feedback loop ratios and its Onset Temperature Difference (TD) as well as the peak pressure of the soundwave produced was recorded. The Onset TD is the temperature difference between the hot side and the cold side of the regenerator when the DEMO 2 Engine first start to produce soundwave. Due to the DEMO 2 Engine has two TA Cores, it is very challenging to ensure the temperatures of both Regenerators are kept constant. Therefore, an Average Onset TD was calculated instead by averaging the Onset TD recorded at each TA Core. Subsequently, the Average Onset TD and the Peak Pressure of the soundwave in each TA Core when the temperature difference between the hot and cold sides of the Regenerator is at 300 °C was plotted for every Feedback Loop Ratio in Figure 5.2.

The desired performance of the DEMO 2 Engine is to have a low Onset TD and a soundwave with high peak pressure. From Figure 5.2, it is observed that the best performance was achieved at a Feedback Loop Ratio of approximately 3.4:1, which is different from the expected optimum Feedback Loop Ratio of 3:1. This indicates that the required total length of the sum of section BC and the length of one TA Core is

lesser than a quarter of the wavelength of the soundwave. Several factors could have contributed to this result. For instance, the uncertainties of the measurements could have affected the estimation of the Feedback Loop Ratio. Besides that, the non-linear effects in the TA Core and the Feedback Loop could affect the ability of the Feedback Loop to perform as expected. Also, Equation (5-1) uses the speed of sound at room temperature of 28 °C. However, when the air inside the TA Cores is heated to a higher temperature, the speed of sound at that temperature is different than the speed of sound at room temperature. This would also increase the uncertainty of the calculation of the Feedback Loop Ratio. Despite of these, Figure 5.2 still managed to show an optimum operating point for the DEMO 2 Engine, where the length of BC and DA can be determined by using Equation (5-2) and selecting a desired operating frequency for the DEMO 2 Engine. Therefore, the procedures described in this section is sufficient to obtain an optimum feedback loop configuration for the DEMO 2 Engine.

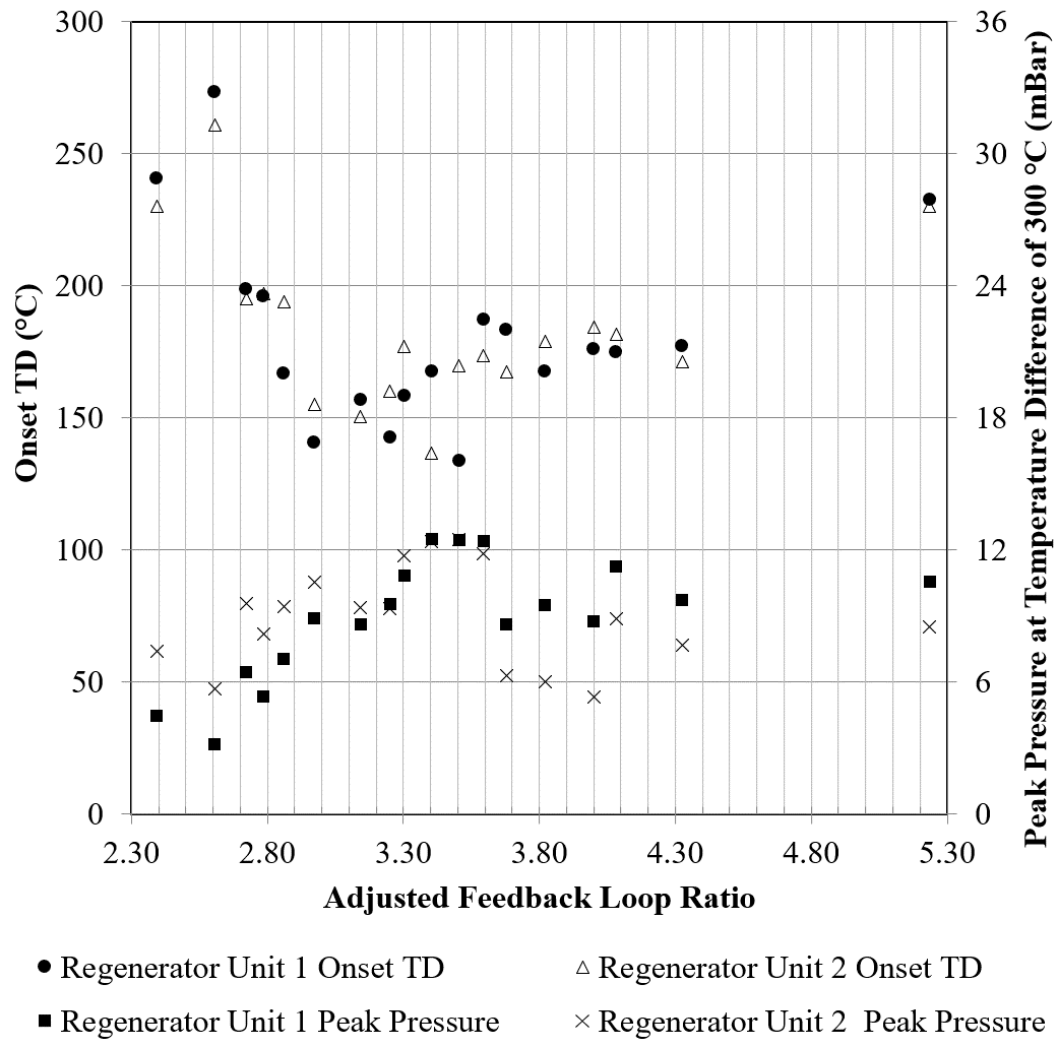


Figure 5.2: Comparison of the DEMO 2 Engine performance at various Feedback Loop Ratios.

5.4 Elbow Effective Length and Diameter

Apart from the components in the TA Core, the effective length of the components in the Feedback Loop is also important in analysing the characteristics of the DEMO 2 Engine. For a straight pipe where plane wave is propagating in it, the acoustic length of the pipe is equalled to its physical length. However, the Feedback Loop of the DEMO 2 Engine consists of straight pipes as well as elbows. Estimating the acoustic length of an elbow proves to be not as straightforward as simply measuring the curvature of the elbow. Usually, there is a tendency to use the centreline length of the elbow as the length of the elbow, as illustrated in Figure 5.3. Despite that, studies have shown that using the outer curvature length of the elbow is a better estimation. Besides that, as a soundwave propagates through an elbow, Eddy flow [111]–[113] will occur at the walls of the elbows, causing a reduction of the effective flow area for the soundwave. Therefore, a method to find an effective length and cross section area to represent the elbows in the DEMO 2 Engine was proposed. Furthermore, determining an effective length and cross section area of the elbows would aid the numerical modelling of the entire DEMO 2 Engine.

In fluid mechanics, it is well known that elbows and bends with larger curvature would cause less losses to the fluid flowing through it. Unfortunately, due to the compact design of the DEMO 2 Engine, the space constraints would only allow the use of a 90° PVC elbow, as shown in Figure 5.3. Hence, only the effects of using a 90° PVC elbow were investigated.

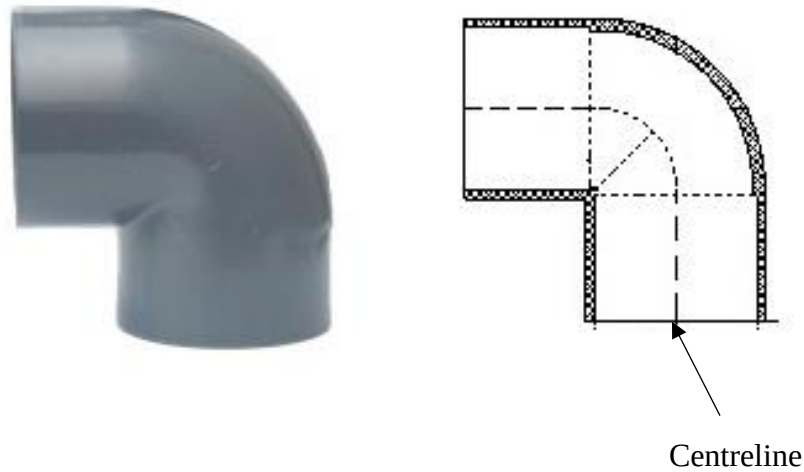


Figure 5.3: A 90° PVC Elbow and its schematic diagram.

To find an effective length and cross section area to represent the 90° PVC elbows used in the DEMO 2 Engine, the elbow was treated as an expansion chamber such that the Impedance Transfer Method can be used. The Impedance Transfer Method is a method that can be used to determine the acoustic impedance variation along a waveguide. For a wave with a pressure oscillation, P , of amplitude, E , travelling in a waveguide with cross-section area, S , and terminated anechoically, as shown in Figure 5.4, P can be written in complex exponential form as,

$$P = E e^{i(\omega t - kx)} \quad (5-3)$$

where i is $\sqrt{-1}$, ω is the angular frequency, t is the time, k is the wavenumber and x is the position along the pipe. Similarly, the particle velocity of the soundwave, v , can also be written in complex exponential form as

$$v = -\frac{1}{\rho} \int \frac{\partial P}{\partial x} dt = \frac{1}{\rho c} E e^{i(\omega t - kx)} \quad (5-4)$$

where ρ is the density and c is the speed of sound.

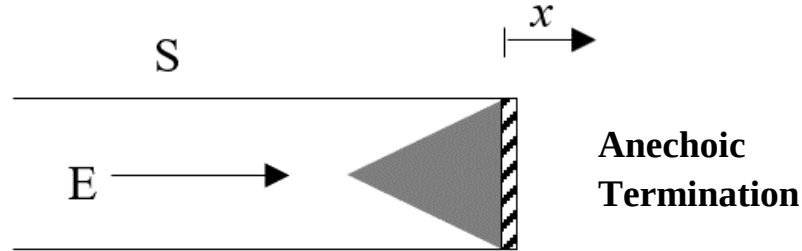


Figure 5.4: A pressure wave travelling in a waveguide with an anechoic termination.

Consequently, the ratio of P to v gives the specific acoustic impedance, $z = P/v$. For the case shown in Figure 5.4, the specific acoustic impedance equals to ρc and this is called the characteristic specific acoustic impedance, $z_o = \rho c$. Also, Equation (5-4) could be multiplied by the cross-section area of the waveguide, S to give the Volume Velocity, U , of the soundwave. Then, the acoustic impedance, $Z = P/U$, would give the characteristic acoustic impedance, $Z_o = \rho c/S$, of the waveguide. For an anechoic waveguide, the specific acoustic impedance and acoustic impedance at all position is equalled to its respective characteristic values.

If the system is not terminated anechoically, then there will be a reflected wave component in the waveguide, as shown in Figure 5.5.

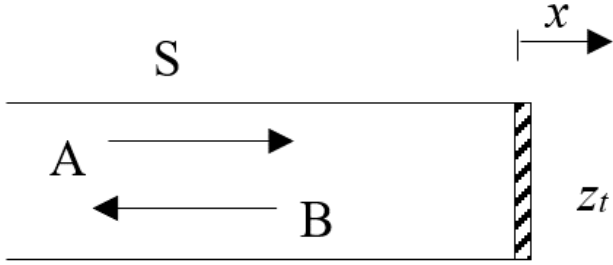


Figure 5.5: Incident and reflected pressure wave in a waveguide with termination impedance, Z_t .

Hence, P can be rewritten as

$$P = A e^{i(\omega t - kx)} + B e^{i(\omega t + kx)} \quad (5-5)$$

By substituting Equation (5-5) into (5-4), the z along the waveguide shown in Figure 5.5 could be computed. For simplification purposes, the time $t = 0$ is considered. Then, at $x = 0$, $z(0)$ is equalled to $P(0)/v(0)$ and the termination specific acoustic impedance, Z_t .

$$z(0) = \frac{P(0)}{v(0)} = \rho c \frac{A + B}{A - B} = Z_t \quad (5-6)$$

Furthermore, the specific acoustic impedance can be normalized by the characteristic acoustic impedance to give a specific acoustic impedance ratio, z' :

$$z' = \frac{z}{z_0} \quad (5-7)$$

Hence, dividing Equation (5-6) by z_o gives $z'(0)$:

$$z'(0) = \frac{z(0)}{\rho c} = \frac{A + B}{A - B} = z'_t \quad (5-8)$$

Next, Equation (5-8) can be rearranged to give:

$$\frac{A}{B} = \frac{z'_t + 1}{z'_t - 1} \quad (5-9)$$

Similarly, the specific acoustic impedance at any arbitrary $-x$ position, $z(-x)$ can be obtained by:

$$z(-x) = \frac{P(-x)}{v(-x)} = \frac{A e^{ikx} + B e^{-ix}}{A e^{ikx} - B e^{-ix}} \rho c \quad (5-10)$$

Then, the specific acoustic impedance ratio at any arbitrary $-x$ position, $z'(-x)$ equals to

$$z'(-x) = \frac{A e^{ikx} + B e^{-ix}}{A e^{ikx} - B e^{-ix}} = \frac{\frac{A}{B} e^{2ikx} + 1}{\frac{A}{B} e^{2ikx} - 1} \quad (5-11)$$

Finally, substituting Equation (5-9) into Equation (5-11) will give the relationship of $z'(-x)$ to the termination specific acoustic impedance, z'_t .

$$z'(-x) = \frac{\frac{z'_t + 1}{z'_t - 1} e^{2ikx} + 1}{\frac{z'_t + 1}{z'_t - 1} e^{2ikx} - 1} \quad (5-12)$$

Hence, if z'_t is known, then the the specific acoustic impedance ratio at any arbitrary $-x$ position could be determined. Further expanding on this, the system of a straight pipe with cross-section area S_1 connected to an expansion chamber with cross-section area S_2 and terminated by an arbitrary impedance as shown in Figure 5.6 is being considered. If the acoustic impedance at location m , Z_m is known, then the specific acoustic impedance ratio, $z'_m = Z_m S_2 / \rho c$ can replace the z'_t term in Equation (5-8).

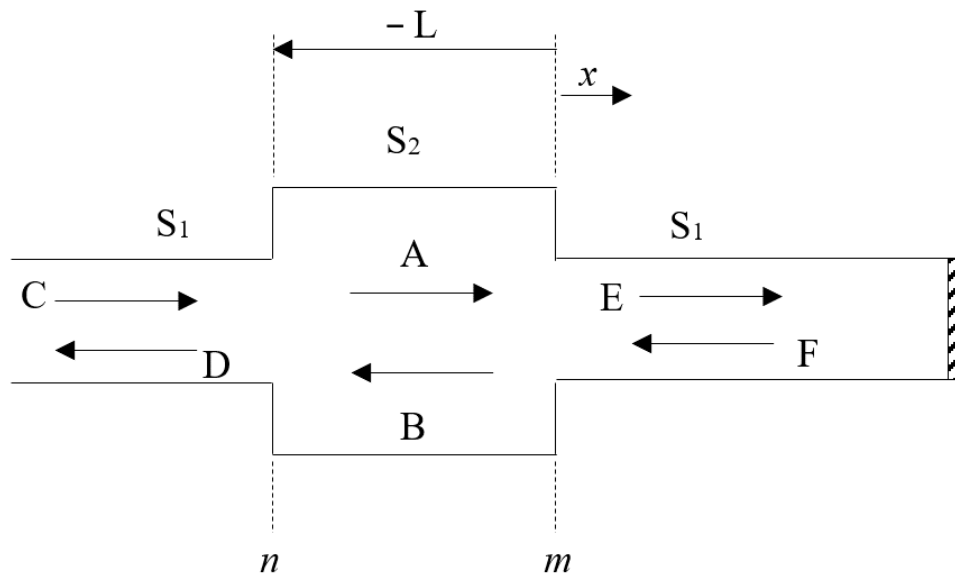


Figure 5.6: A Straight pipe with an expansion chamber of length L .

Consequently, the specific acoustic impedance ratio at location n , z'_n can be obtained from Equation (5-12) by replacing $-x$ with $-L$ where L is the length of the expanded section. Then, z'_n is related to the acoustic impedance at location n , Z_n by $z'_n = Z_n S_2 / \rho c$. If Z_n and S_1 are both known quantities, then the only unknown quantities left are S_2 and L , which is the cross-section area and the length of the expansion chamber respectively. This has set up the suitable conditions to treat the elbows in the DEMO 2 Engine as an expansion chamber to determine an effective length and cross-section area to represent the elbows. An elbow was placed in the centre of a straight pipe with 4 pressure sensors flush mounted to the pipe at both the upstream and downstream to the elbow. A loudspeaker was used as the sound source to the system. This experiment set up enables the acoustic impedances at locations m and n to be obtained by the MMWDM as described in Section 3.6.2. Then, S_2 and L was obtained using an iterative method. The experiment was repeated for various frequencies to obtain the relationship of the effective length and cross-section area with frequency, as shown in Figure 5.7.

Referring to Figure 5.7 (a) and (b), the straight line indicates the measured centreline length of the elbow and the measured diameter of the elbow respectively. Hence, at lower frequency range, the effect of the elbow to the soundwave is as if the soundwave is propagating through an expansion with an extended length. Besides that, as the frequency increases, the effect of the elbow tends towards a straight section with an equal diameter. This also suggests that at frequency greater than 80 Hz, the effect of the elbow becomes less dominant.

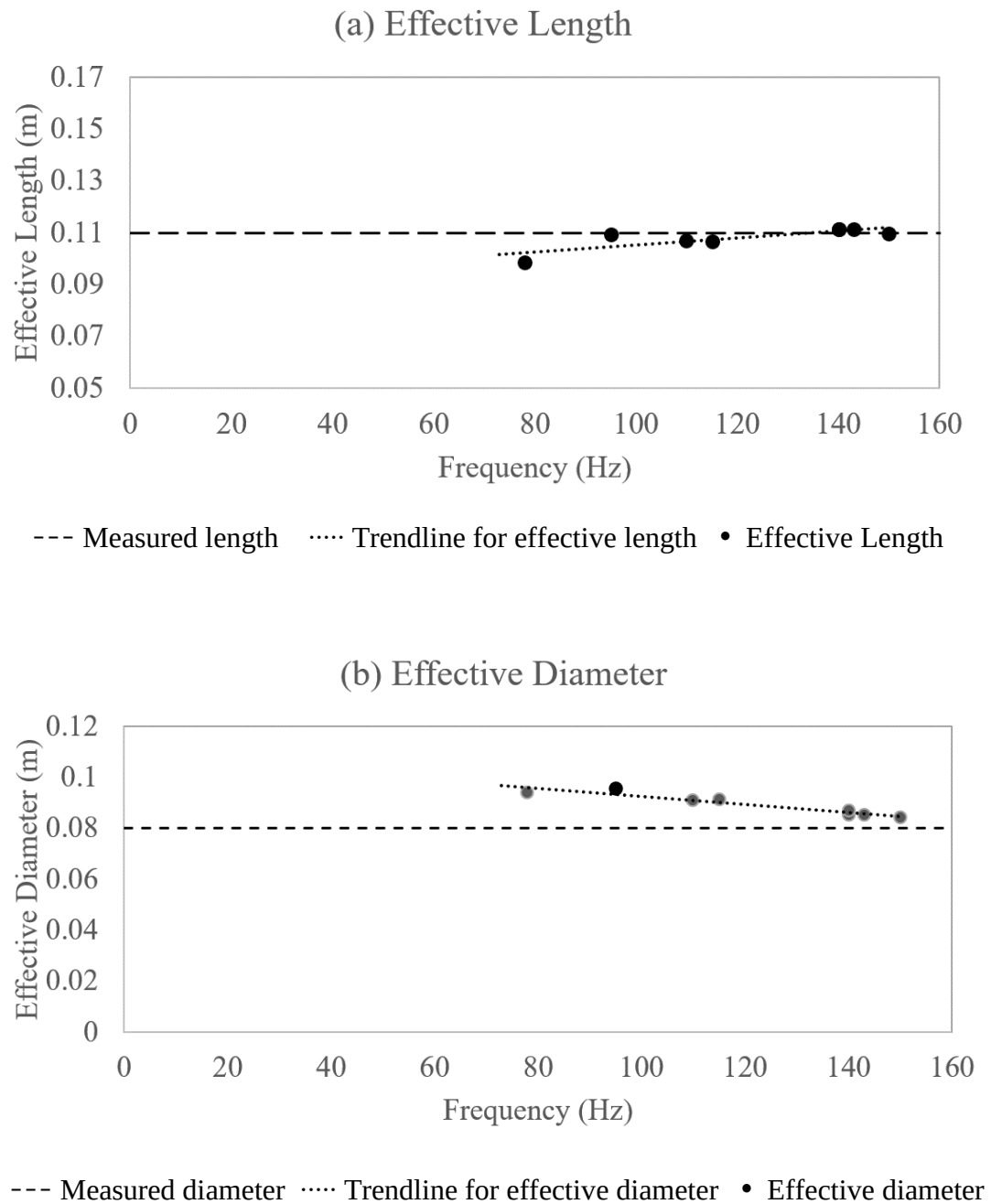


Figure 5.7: The (a) effective length and (b) effective diameter of the elbow at various frequencies.

5.5 Chapter Conclusion

A method to find an equivalent length for the TA Core was developed. The equivalent length was used in the calculation of the Feedback Loop Ratio and the optimum Feedback Loop Ratio was found to be 3.4. Furthermore, an effective length and diameter for the elbows used in the DEMO 2 Engine was also determined by using the Impedance Transfer equation and treating the elbow as an expansion chamber. Lastly, these effective lengths and diameter were used to aid the DELTA EC modelling process.

CHAPTER 6

TRANSFER MATRIX

6.1 Introduction

To characterize the acoustic losses in the DEMO 2 Engine, the acoustic properties of its components were determined. In CHAPTER 2, the definitions of Transmission Coefficient, Reflection Coefficient and Absorption Coefficient were described. In acoustic engineering, these coefficients were used to characterize the performance of acoustic materials. Conveniently, these coefficients could be compiled into a matrix form, called the Transfer Matrix. The measurement techniques to obtain the Transfer Matrix of an acoustic material were adapted for use on the acoustic components in the DEMO 2 Engine. Besides that, the effects on the Transfer Matrix under the presence of heat input to the DEMO 2 Engine were also investigated.

6.2 Elbow

As mentioned in previous chapters, the use of elbows in the acoustic network of the DEMO 2 Engine is unavoidable. Due to that, the acoustic losses caused by the elbow were investigated. In CHAPTER 5, the procedures to determine an effective length and cross-section area of the elbow was described. Those are properties that affects the

acoustic network of the DEMO 2 Engine. In other words, obtaining the effective length and cross-section area of the elbow aids the investigation on the ability of the DEMO 2 Engine acoustic network to provide an optimum acoustic environment for the Regenerator to meet the Rayleigh's criterion. In contrast, obtaining the Transfer Matrix of the elbow investigates the acoustic energy losses as the soundwave produced by the DEMO 2 Engine propagates through the elbow.

Hence, the 2-source method to determine the Transfer Matrix as described in Section 3.6.3 was used for the elbow. For the sound source, white noise was not used as the effects at frequencies above the operating frequency range of the DEMO 2 Engine is not within the objectives of this project. Instead, a mono-frequency sound was provided by the loudspeaker and the experiment was repeated at various frequencies within the interested frequency range. Furthermore, the elbow is located at the midpoint of the upstream and downstream pressure sensors to take advantage of its symmetry. By doing so, only one source is needed to conduct the experiment. This is accomplished by swapping the pressure sensor readings from upstream to downstream, and vice versa, as the second source. This can be expressed in mathematical form by using the following set of equations and the annotations from Equation (2-10).

$$\begin{aligned} \begin{bmatrix} P^a \\ V^a \end{bmatrix}_m &= \begin{bmatrix} P^b \\ V^b \end{bmatrix}_n \\ \begin{bmatrix} P^a \\ V^a \end{bmatrix}_n &= \begin{bmatrix} P^b \\ V^b \end{bmatrix}_m \end{aligned} \quad (6-1)$$

Thus, Equation (2-10) becomes

$$\begin{bmatrix} P_m^a & P_n^a \\ V_m^a & V_n^a \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} P_n^a & P_m^a \\ V_n^a & V_m^a \end{bmatrix} \quad (6-2)$$

After obtaining the Transfer Matrix of the elbow at various frequencies, the Transmission Coefficient and Reflection Coefficient was plotted against frequency, as shown in Figure 6.1. The Transmission Coefficient of the Elbow was found to be 0.99 and within an uncertainty range of 5% for all tested frequencies. This result show that the acoustic energy lost is negligible as the soundwave produced by the DEMO 2 Engine propagates through the elbow. This result is also consistent with the findings from other research [114], [115].

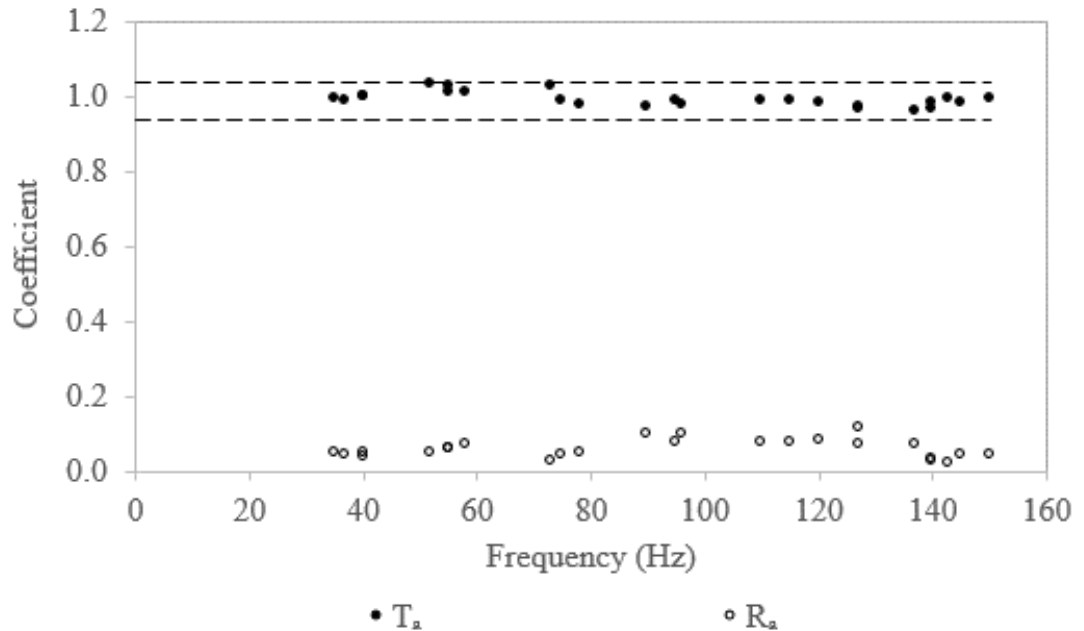


Figure 6.1: The Transmission Coefficient and Reflection Coefficient of the Elbow at various frequencies.

Apart from that, with a Transmission Coefficient of 0.99, the expected Anechoic Reflection Coefficient is 0.01. However, the Anechoic Reflection Coefficient shown in Figure 6.1 is 0.1. This discrepancy is due to an Anechoic Termination was not used in the experiment set up. In addition, due to the value of the Anechoic Reflection Coefficient to be measured is very small, the accuracy of the measurement is very sensitive to errors arising from the experiment set up. In other words, the sensitivity of the experiment set up is not sufficient to measure very small values. Despite that, the Transfer Matrix could also be used to determine the Hard Wall Reflection Coefficient, as shown in Figure 6.2.

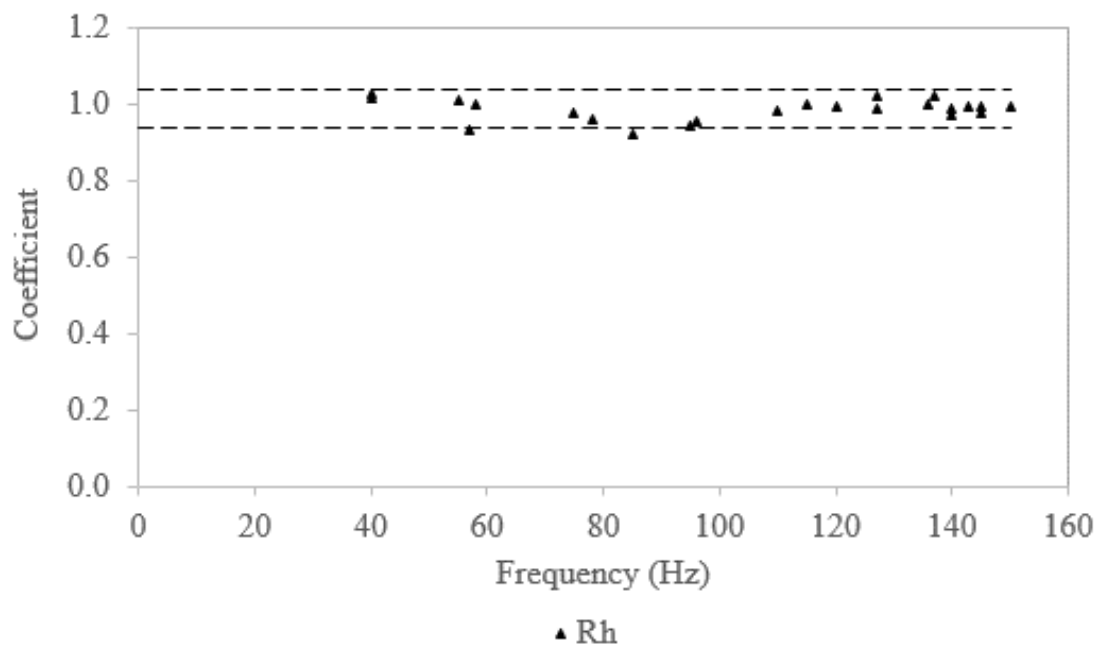


Figure 6.2: The Hard Wall Reflection Coefficient of the Elbow.

Since the value of the Transmission Coefficient is 0.99, the expected value for the Hard Wall Reflection Coefficient should be close to 0.99 as well. This expectation is due to the definition of both coefficients. From Figure 6.2, the Hard Wall Reflection Coefficient of the elbow is 0.99 and within an uncertainty range of 5%. Therefore, from Figure 6.1 and Figure 6.2, it can be deduced that the elbow causes negligible losses and reflection to the soundwave produced by the DEMO 2 Engine.

6.3 U-Bend

Due to the compact design of the DEMO 2 Engine, the elbows used in the Feedback Loop are used other to form a U-Bend. Two identical U-Bends are used in the DEMO 2 Engine, each made up of two 90° elbows connected together by a 30-cm length straight PVC pipe section. The Transfer Matrix of the U-Bend was determined using the same procedure as discussed in Section 6.2 with the U-Bend replacing the elbow. The coefficients of the Transfer Matrix of the U-Bend were also plotted against frequency as shown in Figure 6.3.

The values for the Transmission Coefficient, Anechoic Reflection Coefficient and Hard Wall Reflection Coefficient of the U-Bend are 0.98, 0.1 and 0.98 respectively for all tested frequencies and within an uncertainty range of 5%. These values are also expected with the same arguments for the case of the Elbow as discussed in Section 6.2. Therefore, from Figure 6.3, it can be deduced that the U-Bend causes negligible losses and reflection to the soundwave produced by the DEMO 2 Engine.

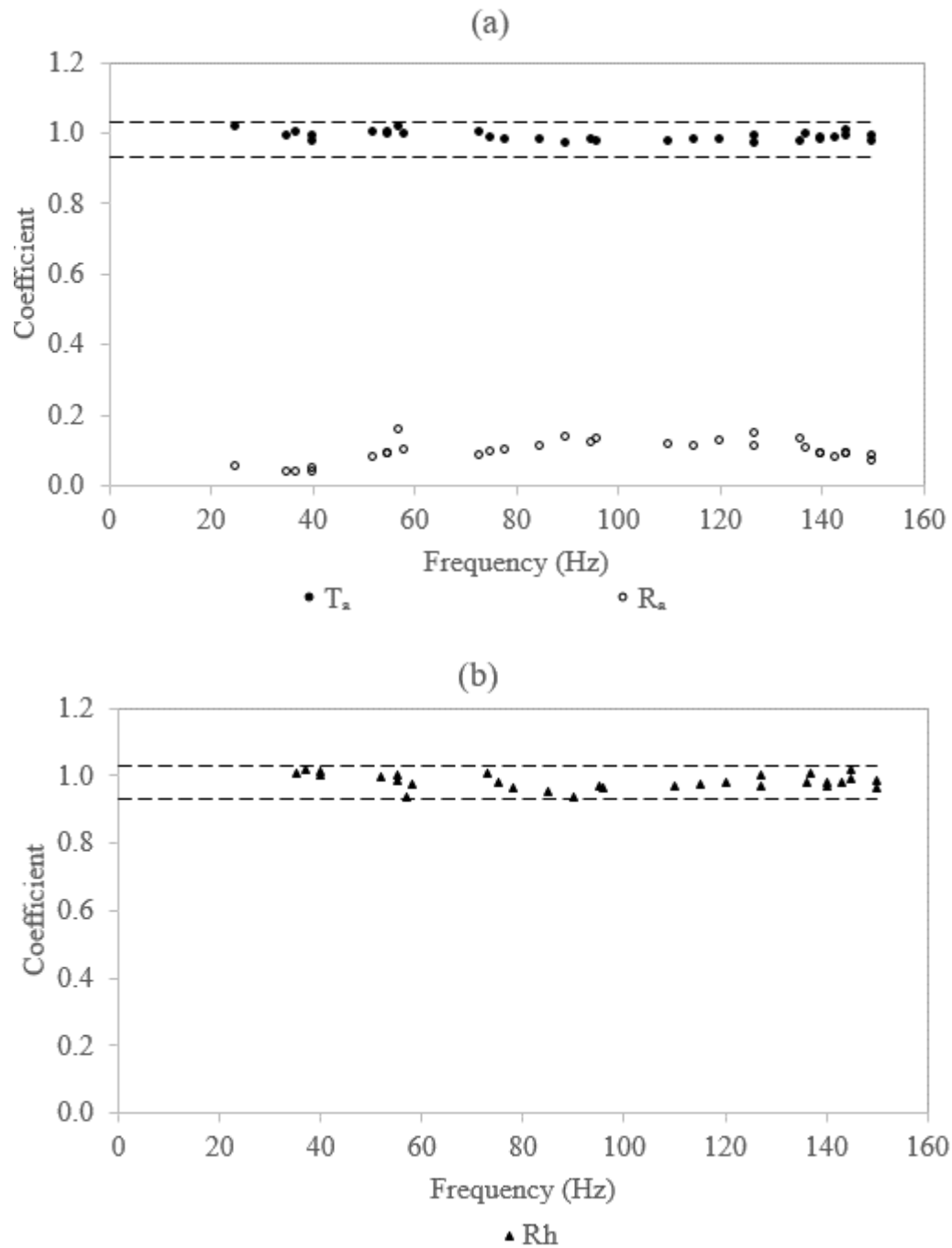


Figure 6.3: (a) The Transmission Coefficient, Anechoic Reflection Coefficient and (b) Hard Wall Reflection Coefficient of the U-Bend at various frequencies.

6.4 TA Core

The advantage of determining the Transfer Matrix is that a series of acoustic components can be considered as a lumped element, whereby the interactions between the components are neglected and only the conditions before and after the components are of interest. This is especially useful to analyse the acoustic properties of a TA Core. The compact design of the DEMO 2 Engine TA Cores coupled with its high operating temperature makes it very challenging to insert sensing devices in the TA Cores to investigate the interactions between the components. Hence, it is much more efficient to determine the Transfer Matrix of the DEMO 2 Engine TA Cores.

The procedure to determine the Transfer Matrix of the DEMO 2 Engine TA Cores differs from the procedure used for the elbows and U-Bends due to the geometry of the TA Cores is not symmetrical. The 2-load Method, as discussed in Section 3.6.3, was used with the 2 loads provided by a closed end and an open end. The sound source was provided by a loudspeaker and mono-frequency soundwave was used for the same reasons as the case for the elbow and U-Bend. The experiment was conducted at various frequencies and for every frequency the experiment was repeated with various heat input into the TA Core. The experiment was conducted separately for both TA Cores. For all the cases with heat input into the HHX, the water cooling of the AHX was turned on as well to mimic the operating conditions of the DEMO 2 Engine. Besides that, all the temperatures shown in Figure 3.4 was measured throughout the experiment. This is to ensure the pressure sensor data were recorded when a steady state is achieved for all

conditions. Usually, it takes up to approximately 45 minutes to 60 minutes for the temperatures and peak pressures to reach steady state. Then, the data were recorded for at least 10 minutes. Finally, the recorded data were post-processed using a MATLAB program to obtain the Transfer Matrix and subsequently the Anechoic Transmission Coefficient, T_a , Anechoic Reflection Coefficient, R_a , and Hard Wall Reflection Coefficient, R_H , for both TA Cores, as shown in Figure 6.4 to Figure 6.7

Referring to Figure 6.4 and Figure 6.6, an Anechoic Transmission Coefficient above 1.0 indicates that the TA Core is amplifying the soundwave as it propagates through the regenerator. This amplification only occurs when more than 360 W of heat was input at the HHX and the soundwave has frequency of less than 60 Hz. The amplification of the soundwave is decreasing as the operating frequency increases with an exception at 70 Hz. This indicates that the optimum frequency for the Regenerator is at 70 Hz, but the change in cross-section area of the TA Core components is acting as an acoustic filter to the system. Hence, it could not provide the optimum acoustic environment for the gas oscillations in the Regenerator to meet the Rayleigh criterion.

Besides that, both TA Cores only showed less than 10% increase of amplification with more than 50% increase of heat input. This indicates that an increase in heat input is not sufficient to overcome the deficit from the acoustic losses. In addition to that, Figure 6.5 and Figure 6.7 shows that there is a high amount of wave reflection from

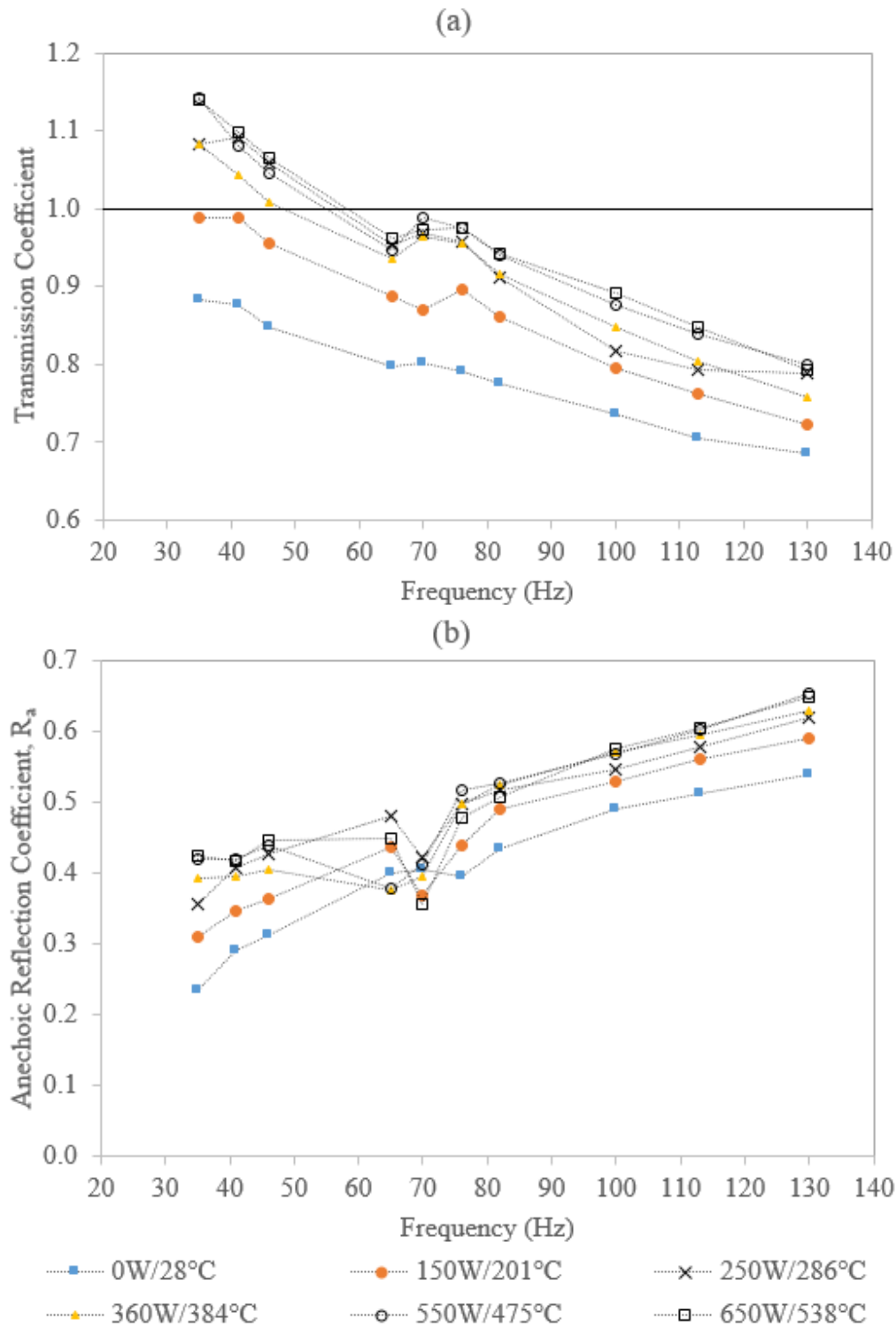


Figure 6.4: The (a) Transmission Coefficient and (b) Anechoic Reflection

Coefficient of TA Core 1 at various frequencies and heat input.

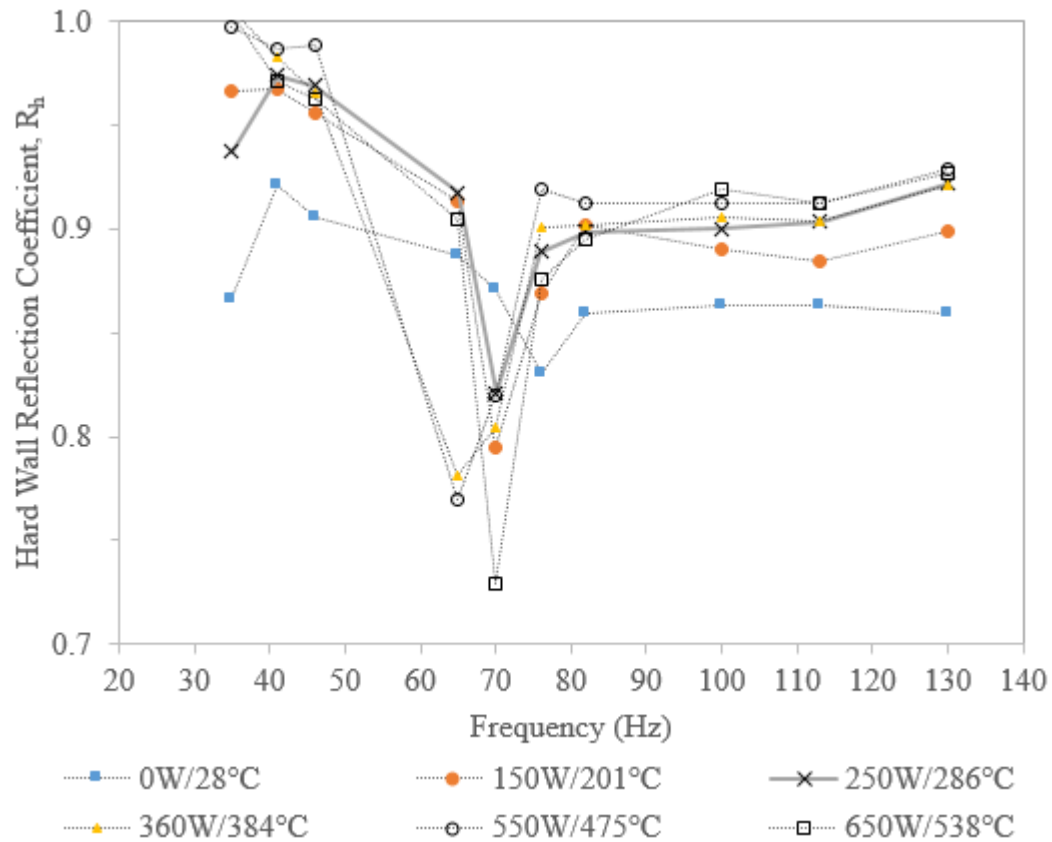


Figure 6.5: The Hard Wall Reflection Coefficient of TA Core 1 at various frequencies and heat input.

the TA Core. This proves that the major contributor of the reflection in the Feedback Loop was caused by the TA Core, but not the Elbows or U-Bends. Therefore, it is essential to alter the design in the TA Core to minimize the changes of cross-section area to the acoustic wave path.

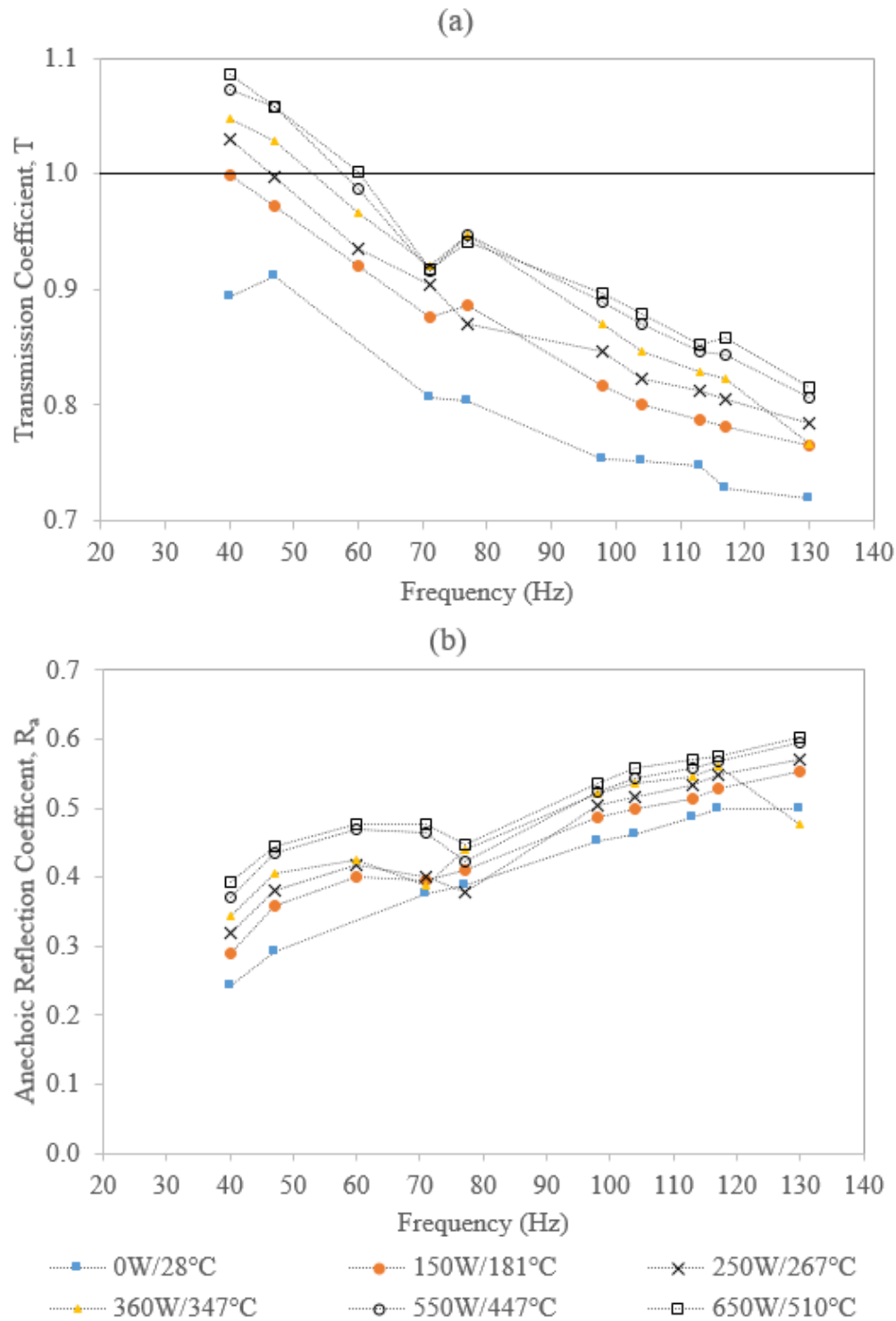


Figure 6.6: The (a) Transmission Coefficient and (b) Anechoic Reflection Coefficient of TA Core 2 at various frequencies and heat input.

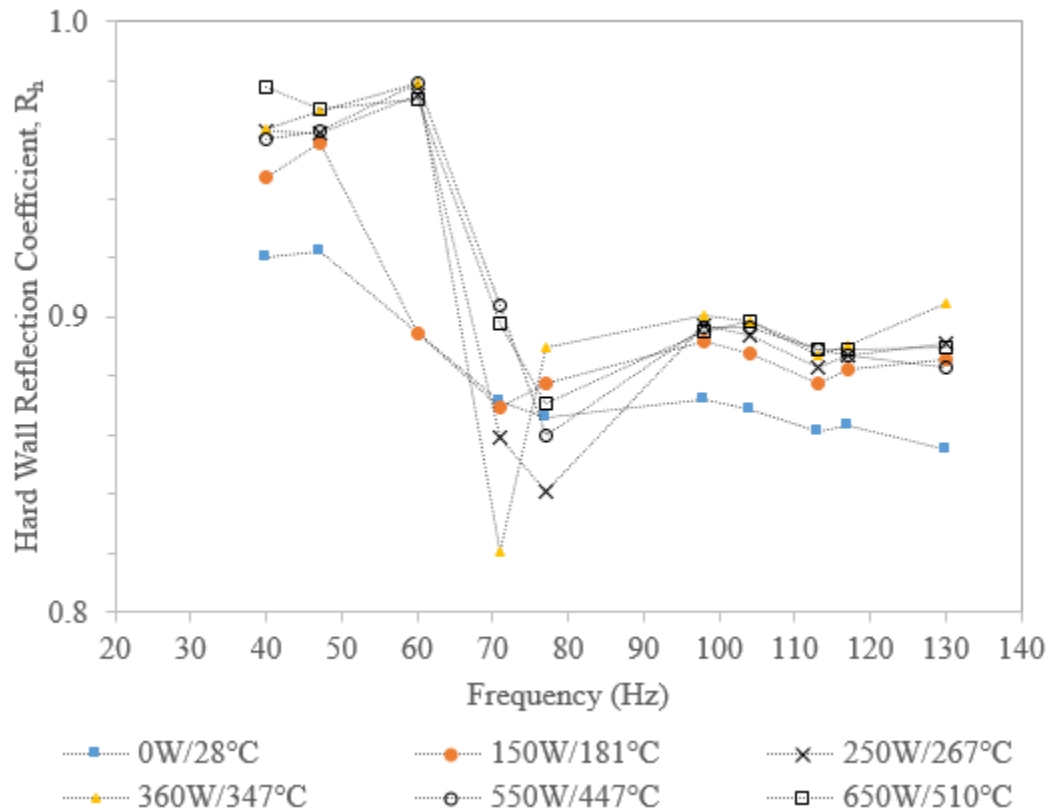


Figure 6.7: The Hard Wall Reflection Coefficient of TA Core 2 at various frequencies and heat input.

6.5 Chapter Conclusion

The Transfer Matrix of the Elbow, U-Bend, and both TA Cores were determined. From the Transfer Matrix, the Anechoic Transmission Coefficient, Anechoic Reflection Coefficient and Hard Wall Reflection Coefficient for the aforementioned components were determined. It was found that the Elbows and U-Bends does not cause significant acoustic losses to the DEMO 2 Engine.

On the contrary, the Transfer Matrix for both TA Cores shows that there is only less than 20% of sound amplification for soundwave below 60 Hz. This indicates that the dimensions of the TA Cores did not provide the optimum acoustic environment for the Regenerator to amplify the soundwave.

CHAPTER 7

DELTA EC MODEL

7.1 Introduction

Based on the review in Chapter 2, it was deduced that using DELTA EC is the most suitable approach to construct a numerical model for the DEMO 2 Engine. The main objective of constructing a DELTA EC model for the DEMO 2 Engine is to investigate the acoustic interactions inside the TA Core, as the experiments conducted could only observe the acoustic conditions in the Feedback Loop. Therefore, the DELTA EC model was constructed such that its predictions of the conditions in the Feedback Loop matches the experiment results. This was accomplished by setting the boundary conditions for the model based on the construction details of the DEMO 2 Engine as well as the operating conditions observed through the experimental investigations. As a result, the DELTA EC model was able to replicate numerically the interactions inside the TA Core, as discussed in this chapter.

7.2 DEMO 2 Engine Components

The concept of a TAE is still considered a recent technology when compared to heat engines such as Internal Combustion Engines and Stirling Engines. Many new

interpretations of the technology are still emerging, leading to the use of a wide range of components. Set against this background, DELTA EC is a software that was written specifically for the thermoacoustic systems used in the Los Alamos National Laboratory. Thus, the functions in DELTA EC do not include all the components used in the DEMO 2 Engine. For components that do not have a built-in function in DELTA EC, the built-in functions for components with the closest similarities were selected instead. Whenever necessary, modifications were made with careful considerations and interpretations to the physical meaning of the functions. The following sections discuss on the selections of the DELTA EC functions to represent the components in the DEMO 2 Engine as well as the modifications and assumptions made. The names of the DELTA EC functions are written in upper case and its detailed descriptions were provided in the DELTA EC Users Guide [79].

7.2.1 Straight Pipe

To model the straight pipe sections, DUCT was used with the measured length and cross-section area of the section. However, during the experiments, it was observed that the air temperature of the Feedback Loop sections adjacent to the TBV is above room temperature, as stated in CHAPTER 4. In these regions, STKDUCT was used instead to allow DELTA EC to vary the air temperature. Besides that, it was also observed that the walls of the pipes at these regions were warm during the experiments. This indicates that there is minor heat loss to the environment through the walls. To consider this effect, TX was used to extract heat from this region. Thus, the Feedback

Loop section adjacent to the TBV was represented by STKDUCT with a TX attached at the end. The length of the STKDUCT and the heat rejected at TX are varied until the air temperature predictions by DELTA EC matches the experiment data.

7.2.2 Elbow

In CHAPTER 5, an effective length and cross section for the elbow was determined. Since DELTA EC do not have built-in functions for elbows, DUCT was used instead with the length and cross-section area obtained from Figure 5.7.

7.2.3 Tuning Volume

The Tuning Volume was modelled using STKDUCT with the measured length and cross-section area of the section. The Tuning Volume is directly connected to the Feedback Loop and it presents a sharp increase in cross-section area to the wave path. To accommodate the effect of this, an IMPEDANCE was added, as this is recommended in the User's Guide to model sharp changes in cross-section area.

7.2.4 AHX

The AHX is a custom-made copper finned tube type radiator. Hence, it was modelled as an array of parallel plates using HX. The distance of the parallel plates was determined by calculating the fin density of the AHX and the thickness was measured using a Vernier Calliper.

7.2.5 Regenerator

The Regenerator was modelled using STKSCREEN. The measured dimensions of the Regenerator were used for the values in STKSCREEN. The wire diameter and density were obtained from its manufacturer specification datasheet to compute the volumetric porosity, ϕ , and hydraulic radius, r_h , from Equation (7-1) and Equation (7-2), respectively [79].

$$\phi = 1 - \frac{\pi n D_{wire}}{4} \times \sqrt{1 + (n D_{wire})^2} \quad (7-1)$$

$$r_h = D_{wire} \frac{\phi}{4(1 - \phi)} \quad (7-2)$$

7.2.6 HHX

By observing the geometry of the HHX, the channels of the HHX could be treated as parallel plates. However, the HX function in DELTA EC is assumed to be so short that only a single integration step was performed from its starting point to its end point, which is not suitable for the DEMO 2 Engine HHX. By analysing the heat transfer processes in the HHX, it was noticed that it is similar to the shell-and-tube heat exchangers as hot air passes through the HHX at one side and heat is transferred through the walls of the HHX to the acoustic air on the other side and in the DEMO 2 Engine. Therefore, VXQ1 was used to model the DEMO 2 Engine HHX. The dimensions used in VXQ1 are the measured dimensions of the HHX.

7.2.7 Thermal Buffer Volume

A unique feature of the DEMO 2 Engine TBV is that it is directly connected to the AHX to remove excess heat from the HHX to prevent heat from entering the Feedback Loop. To model this in DELTA EC, a combination of PX and STKDUCT were used. This is illustrated in Figure 7.1. In addition, it was assumed that the heat removed rate at the TBV is uniform across its length. However, DELTA EC also treats PX to be so short that only a single integration step was performed. Thus, the combination of PX and STKDUCT were repeated four times and connected in series with the total length equals that of the TBV. At the end of the TBV, an IMPEDANCE was used to consider the effects of the sudden reduction in cross-section area as the wave exits to the Feedback Loop.

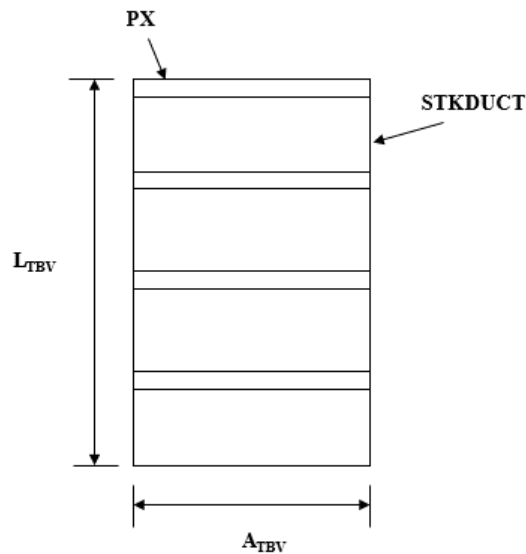
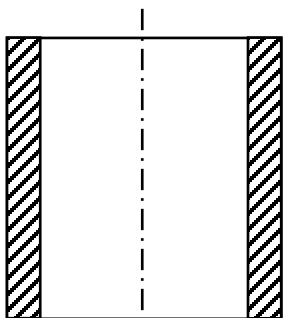
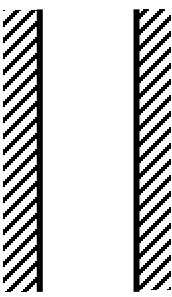


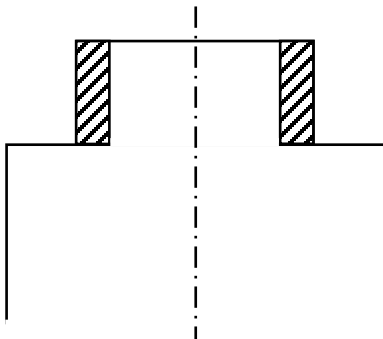
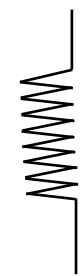
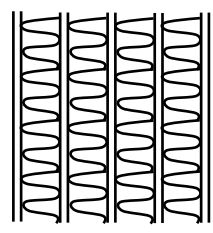
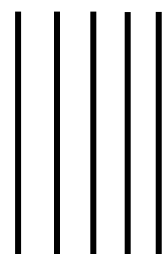
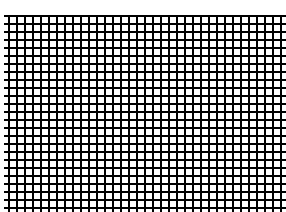
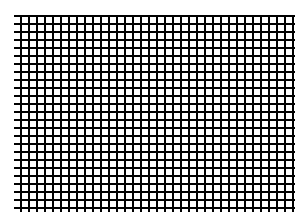
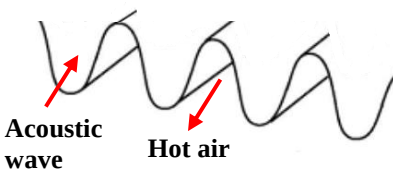
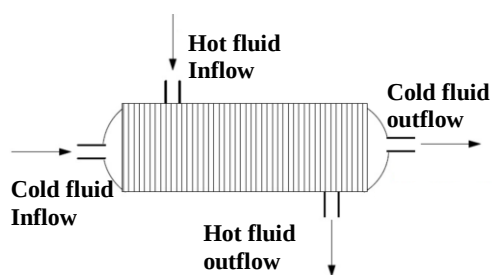
Figure 7.1: Combination of PX and STKDUCT.

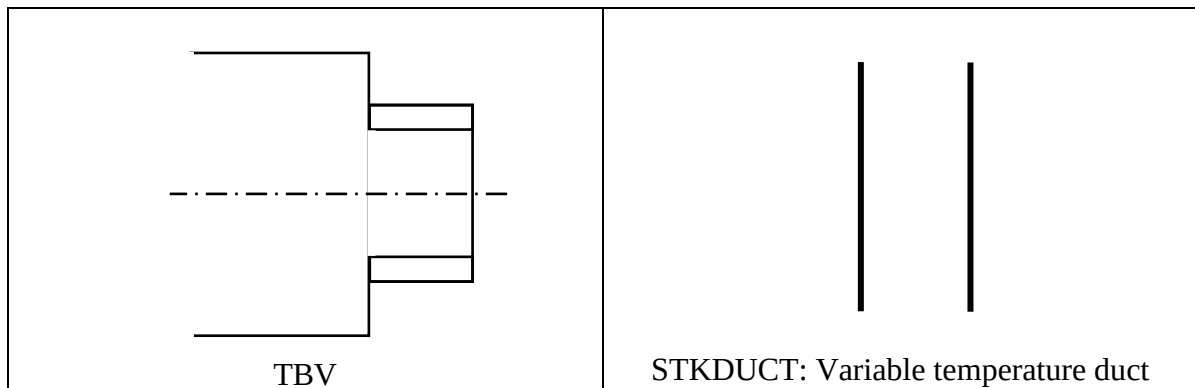
7.2.8 Summary

The summary of the DELTA EC functions for each component of the DEMO 2 Engine is presented in Table 7.1 below. It is worth mentioning that functions with the closest similarities were used for components without a built-in function (such as AHX, HHX and TBV) after careful considerations as well as appropriate validation exercises with respect to the experimental measurements. The respective validations and results analysis are presented in Section 7.4. Hence, these models are deemed as valid representatives for the engine components in the numerical modelling studies. Next, the *Guess and Target* feature of DELTA EC was used to match the results output by the model to the experimental results in Section 7.3.

Table 7.1: Summary of DELTA EC functions used to model Engine components.

Physical Component(s)	DELTA EC Functions
 <p>PVC Pipe</p>	 <p>DUCT = insulated duct</p>

 <p>Connection between TA CORE and Feedback Loop</p>	 <p>IMPEDANCE: Change in impedance of the soundwave</p>
 <p>AHX (Plate-fin heat exchanger)</p>	 <p>PARALLEL PLATES</p>
 <p>Regenerator (wire mesh)</p>	 <p>REGENERATOR</p>
 <p>HHX (Corrugated plate heat exchanger)</p>	 <p>SHELL-TUBE HEAT EXCHANGER</p>



7.3 Modelling Process

Besides the functions discussed in Section 7.2, additional functions and features of DELTA EC were needed to complete the model. As stated in CHAPTER 2, an important feature of DELTA EC is its ability to *Guess* and *Target* the values in the model. This feature is used throughout the modelling process and it is discussed in this section.

To initialize the model, a starting point was specified using BEGIN. In addition, due to the acoustic network of the DEMO 2 Engine forms a closed loop, the conditions of the starting point of the model must be linked explicitly to the end point. To accomplish this, the BEGIN is connected to TBRANCH so that DELTA EC will split the calculations into two branches. Then, these two branches are reconnected together to form a closed loop. The reconnection is done by inserting a SOFTEND in one branch for DELTA EC to recognize this as the end of the branch and the SOFTEND is

connected to a UNION for DELTA EC to recognize the location of the reconnection point. Furthermore, the UNION was connected to a HARDEND and the impedances of the HARDEND were targeted to zero to complete the reconnection. This is the recommended method as stated in the User's Guide. The BEGIN point was selected at the midpoint of a pressure sensor pair. This is so that the measured values of the conditions at this point could be used for the model. Also, the values of the impedances at TBRANCH were obtained through experimental measurements. With experimentally obtained values inserted at the BEGIN and TBRANCH, DELTA EC easily predicts the right conditions along the DUCT sections until the model encounters the STKDUCT for the section immediately before the TA Core.

The length of the STKDUCT was varied until the model predicts the right temperature at the thermocouple locations. Subsequently, the next component is the TBV. The TBV is also represented by a STKDUCT and its connected to an IMPEDANCE. The values for the IMPEDANCE was set as *Guesses*, which will be determined by DELTA EC. The next component is the TX for the AHX. The value for the heat rejected at the AHX could not be obtained from the experiment measurements because the AHX also removes heat from the TBV. Hence, the total amount of heat rejected to the water cooling is the sum of the heat rejected at the AHX and the heat removed from the TBV. Thus, the heat rejected by the AHX was varied until the temperatures of the Regenerator matches the experimental results. Consequently, the heat input at the HHX was also varied until its solid wall temperature matches the experimental results. Next,

the total heat removed by the TBV sections was determined as the difference between the heat input at the HHX and the heat rejected at the AHX. However, the experiment results indicate there is heat leakages into the Feedback Loop. Thus, an RPN segment was added before the TBV section to calculate the heat leakage,

$$\text{Heat Leakage} = \frac{\text{Heat Input at HHX} - \text{Heat Rejected at AHX}}{\text{Heat Removed from TBV}} \quad (7-3)$$

The amount of heat leakage was set as a *Guess*, and the temperature at the STKDUCT section was set as a *Target* to match the experimental data. Besides that, the values for the IMPEDANCE at the end of the TBV was also set as *Guesses* and the Peak Pressures at the locations of the sensors downstream of the TA Core was set as *Targets*. The entire modelling process of the TA Core involved many iterations, trial and errors, and the use of the *Guess and Target* feature of DELTA EC until the model predicts the conditions of the Feedback Loop downstream to the TA Core that matches the experiment results. Then, the entire process was repeated for the other TA Core. Finally, after both TA Cores are modelled, the final iteration is to *Target* the values for the HARDEND at the UNION to zero to reconnect the end of the model to the BEGIN to form the closed loop of the DEMO 2 Engine.

7.4 Validation and Results Analysis

To validate the DELTA EC model, the results output by the model were compared with the experimental results, as shown in Figure 7.2 and Figure 7.3. The results output by the model shows good agreement with the experimental results. Even though the model was made to match the experiment results, only the Peak Pressure data were used as *Targets* during the modelling process. Hence, with the model output showing good agreement with other experiment data besides the Peak Pressure, it can be deduced that the model is a valid representation of the DEMO 2 Engine. Consequently, the results output by the model can be further analysed to complement the experiment results.

Due to the small pores of the regenerators, the performances of a travelling wave TAE are prone to viscous losses across its regenerator. One method to reduce the viscous losses across the regenerator is to reduce the particle velocity of the gas oscillating through the regenerator. From Figure 7.2 (b), it can be observed that the particle velocity of the gas as it enters the TA Core is not at its minimum, which occurred at the location of approximately 1.3 m. Therefore, the TA Cores position should be altered such as it will be at the minimum point of the particle velocity oscillation.

Apart from that, Figure 7.3 shows that there are sound amplifications across both regenerators. Although this is a desired effect, the maximum sound power in the Feedback Loop is only 3.5 W. This indicates that the acoustic power generation of the DEMO 2 Engine is very poor. Besides that, there is a large decrease in acoustic power

as the sound wave enters TA Core 1 and an increase as the soundwave exits the TA Core. These results are not expected as the sound amplification should only occur across the Regenerator. However, this can be explained as the model indicates there is a sound leak within TA Core 1, or in electrical circuit analogy, there is short circuit in TA Core 1. Referring to Figure 3.4, the sealing between the TBV and the Tuning Volume could have failed. As a result, there is an insignificant net increase in acoustic power across TA Core 1. Actually, this revelation is not unexpected as during the preliminary experiment stages, it was noticed that the DEMO 2 Engine could not produce sound oscillation when only the HHX in TA Core 1 was heated. In contrast, the DEMO 2 Engine produces sound oscillations when only the HHX in TA Core 2 were heated.

In addition to that, the model could also be used to determine the heat flow values in Figure 4.1. The *Guess and Target* iteration process converged to a solution that could be used to complement the experimental results for the heat flow as well. This further enhance the validity of the DELTA EC Model.

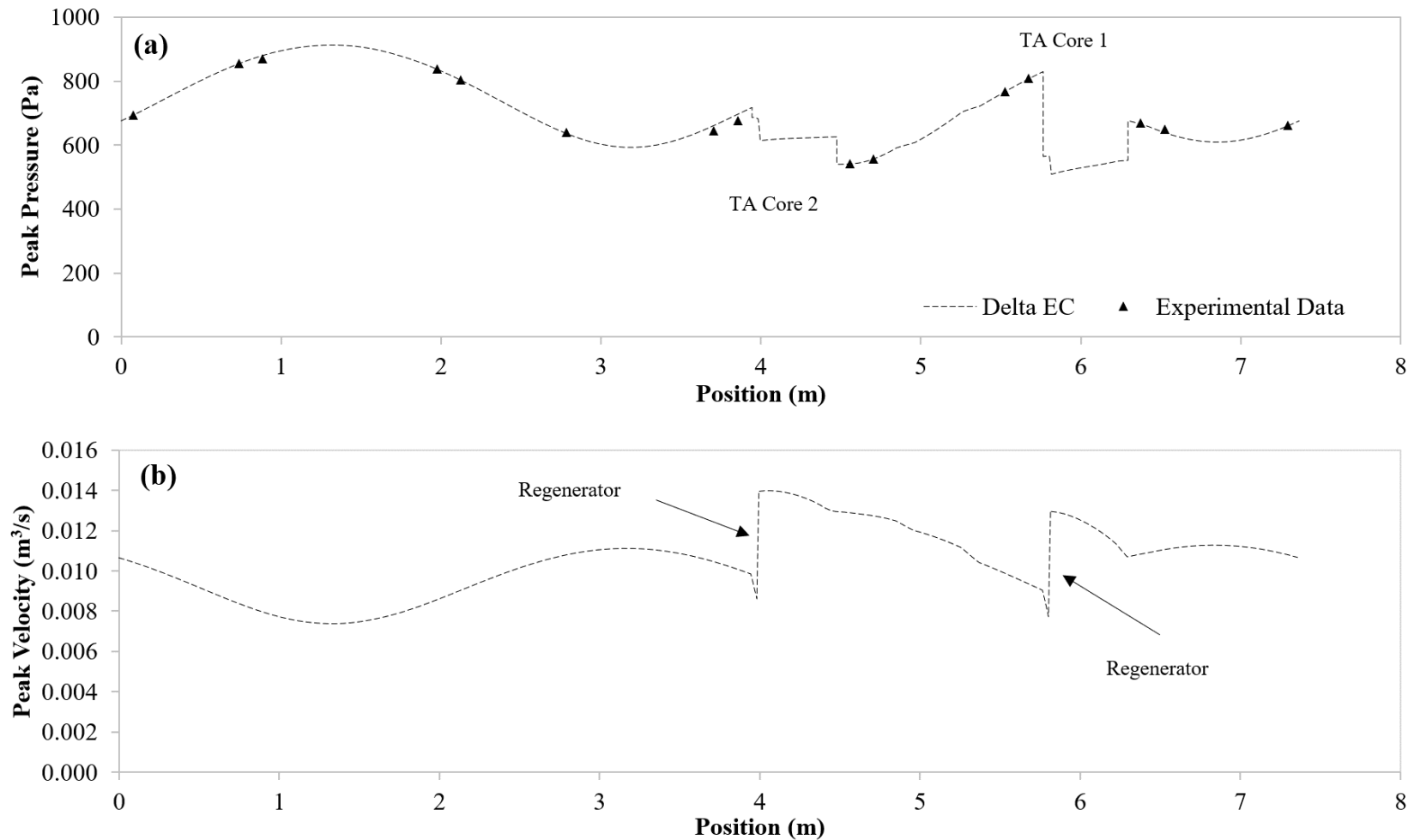


Figure 7.2: (a) Comparison of the DELTA EC output and the experimental results in terms of peak pressure and (b) DELTA EC output for peak velocity.

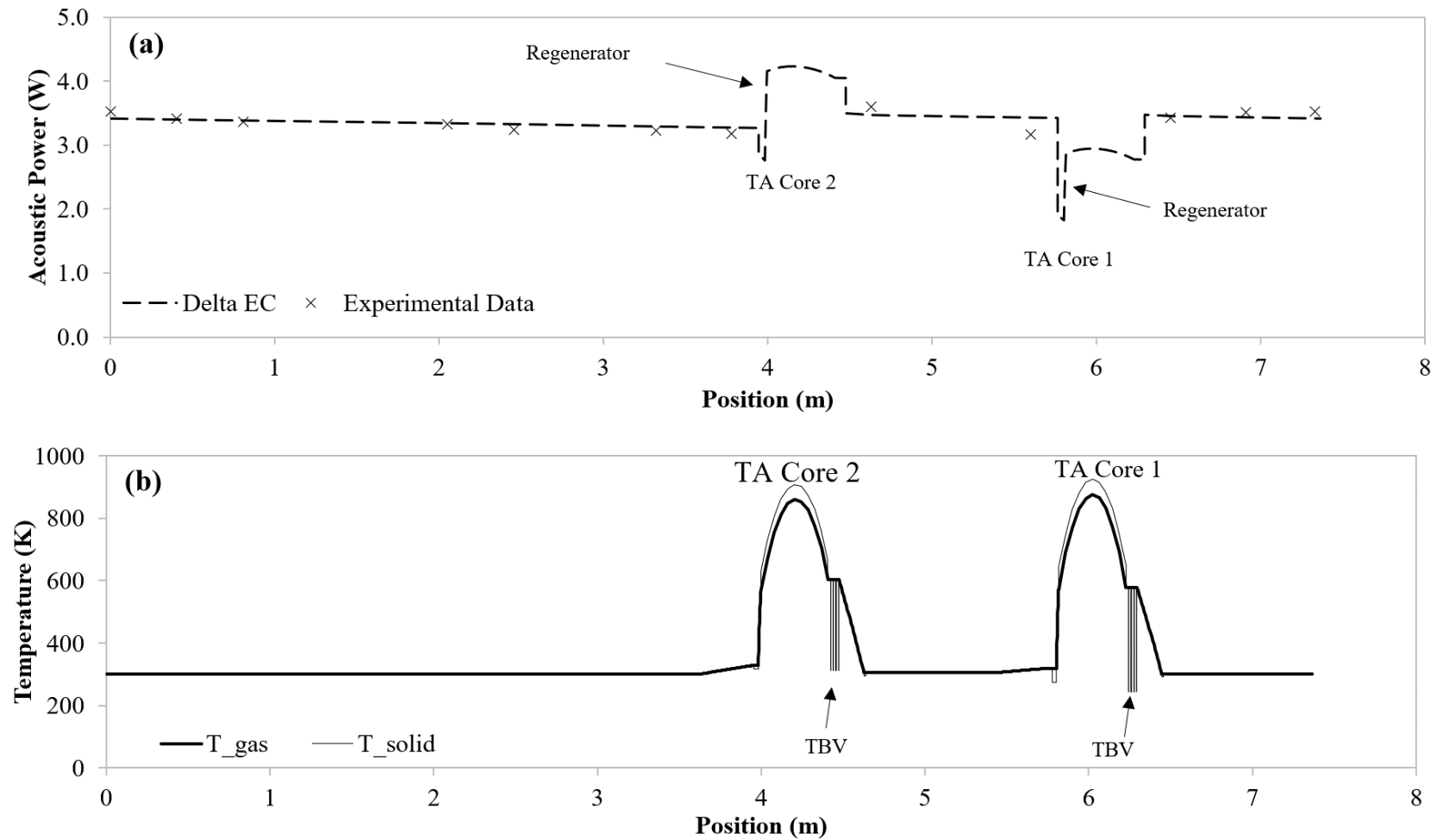


Figure 7.3: (a) Comparison of the DELTA EC output and the experimental results in terms of acoustic power and (b) DELTA EC output for temperature.

7.5 Chapter Conclusion

The steps taken to construct the DELTA EC model for the DEMO 2 Engine was described. The *Guess and Target* feature of DELTA EC was used to match the results output by the model to the experimental results. Also, for components that do not have a built-in function in DELTA EC, the functions with the closest similarities were used instead. Based on the validation results obtained in Section 7.4, it is demonstrated that the model outputs using the functions with the closest similarities are in good agreement with the experiment measurements. Therefore, this approach proves to be valid to construct a numerical model for further analysis on the DEMO 2 Engine with careful considerations on the assumptions and modifications made. The output results of the model were also used to complement the findings from other chapters.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.1 Introduction

The work in this project has successfully tackled major research problems that were encountered in the development of a thermoacoustic engine, namely the DEMO 2 Engine. This research aims to provide a quantitative description of the types of losses found in a thermoacoustic engine. The losses are categorized into two main categories which are heat transfer losses and acoustic losses. A systematic approach was undertaken to characterize both type of losses and its influence on the final performance of the DEMO 2 Engine were analyzed. The outcomes of this research are not only able to aid the advancement of the DEMO 2 Engine, but it is also applicable to other development of thermoacoustic systems. This chapter presents the outcomes of this project and also the recommendations made for future development of thermoacoustic engines.

8.1.1 Heat Transfer Performances the DEMO 2 Engine

A Heat Flow Network was constructed to describe the heat flow in the DEMO 2 Engine. It was observed that the DEMO 2 Engine loses significant amount of heat to its surroundings and is unable to input heat to the oscillating gas effectively. Besides that, the TBV of the DEMO 2 Engine were unable to prevent heat from entering the Feedback Loop. This would in turn affect the acoustic performances of the DEMO 2 Engine.

The Heat Flow Network has shown the importance of heat insulation for a thermoacoustic engine. Heat insulation is not only vital in reducing heat loss to the environment, but also it is important to minimize the parasitic heat losses between the components of the thermoacoustic engine. The working principle of a thermoacoustic engine requires a sharp change in temperature over a short distance of space, hence the insulation between the components is essential to provide the optimum conditions for the thermoacoustic oscillations to occur. The Heat Flow Network proves to be an essential tool to investigate the heat flow path within a thermoacoustic system and to identify the main source of parasitic heat losses.

8.1.2 Acoustic Performances of the DEMO 2 Engine

In addition, the acoustic performances of the components in the DEMO 2 Engine were evaluated. It was found that the elbows in the feedback loop does not cause significant acoustic losses nor wave reflections. The usage of elbows and bends are unavoidable

in most designs of thermoacoustic systems that involves a closed loop. Hence, it is significant to report that despite the sharp elbows used in the DEMO 2 Engine, it did not cause significant losses to the DEMO 2 Engine performances.

However, it was also found that elbows will affect the effective length of the closed loop, hence this effect must be taken into considerations when determining the length of the loop.

On the other hand, the acoustic performances of the TA Cores were found to be the major contributor to the losses in the DEMO 2 Engine. It was observed that the geometry of the TA Core causes significant losses and reflection of the sound wave. Due to that, the TA Core was not able to provide the optimum conditions for sound generation. This finding shows the importance of a properly designed TA Core and the flaws of the DEMO 2 Engine design should be avoided. The main design flaw of the DEMO 2 Engine is it has many changes in cross section area, which presents a change in acoustic impedance to the propagating wave and hence causes a wave reflection. Such feature should be avoided in future designs of thermoacoustic systems.

Furthermore, it was also found that there is air leakage within TA Core 1, causing significant losses to its performances. Due to the inability of TA Core 1 to produce significant sound power, its presence is analogous to a load being applied to TA Core 2. Therefore, all the amplifications from TA Core 2 is used to overcome the losses

within the Feedback Loop as well as the load presented by TA Core 1. This can be used as a reminder to future researchers of thermoacoustic systems that involves multiple TA Cores that checking the functionality of every TA Core is also an important step in troubleshooting for problems in the thermoacoustic system.

8.1.3 Numerical Model

The advantages of having a numerical model of the thermoacoustic system is adamant as shown in this project. A different approach to construct a DELTA EC model for the DEMO 2 Engine was developed. The sound pressure in the Feedback Loop and the temperatures of key components within the TA Cores were measured and used as an input and boundary conditions to the DELTA EC model. With the DELTA EC model, the behavior of the sound wave inside the TA Cores was identified, whereby experimental probes or sensors are hard to access such areas. Hence, constructing a numerical model of a thermoacoustic systems is essential in its development.

8.2 Recommendations for Future Work

The problems encountered in the development of the DEMO 2 Engine were documented and the solution approach was presented in this thesis such that future researchers could apply this knowledge to other thermoacoustic systems. Based on the outcomes of this project, the following work are recommended to further improve the understanding of the thermoacoustic phenomenon and to continue the development of the thermoacoustic technology.

8.2.1 A Detailed Numerical Model

As the performance level of thermoacoustic engine continues to increase, the non-linear effects in a thermoacoustic engine is expected to play an increasingly major role in affecting the performance of the thermoacoustic engine. The modelling method presented in this thesis could be used as a basis for constructing more complicated numerical models. This project has shown that it is worthwhile to construct a numerical model based on existing empirical data, instead of beginning with a numerical model and subsequently constructing an experiment rig to validate the results of the model.

8.2.2 Acoustic to Electrical Energy Converter

Besides that, to make use of the acoustic power produced by a thermoacoustic engine, it first has to be stored or converted to an alternative form of energy. The most promising approach at the time of writing is to convert the sound energy to electrical energy. Therefore, an effective acoustic to electrical energy converter is required. Based on the findings of this project, the Impedance Transfer method proves to be an effective and convenient method to characterize the acoustic properties of the components in a thermoacoustic system. Hence, it is recommended that the acoustic properties of any potential acoustic to electricity converter is has to first be determined before it is installed to a thermoacoustic system. In addition, the optimum location to install the converter could also be determined using the Impedance Transfer method.

8.2.3 Modifications to the DEMO 2 Engine TA Core

Lastly, the concept of the DEMO 2 Engine has shown promising potential in its initial development stages. However, the pursue of a compact design for the DEMO 2 Engine has led to many constraints and limitations for its Regenerator to perform to its fullest potential. In view of that, a well-insulated TA Core is needed to prevent heat loss to the surroundings and minimize the parasitic heat losses within its components. Besides that, the TA Core was found to be the major contributor affecting the DEMO 2 Engine performance. As a result, it is recommended that the design of the TA Cores has to be improved to eliminate the frequent changes in cross section area.

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APPENDICES

A. Rectification works on the DEMO 2 Engine

After the preliminary experiments, the TA Cores were disassembled to perform a forensic investigation on the components in the TA Core. Referring to Figure A1, it is obvious that the burnt mark indicates an uneven heating of the regenerator.



Figure A1: Burnt marks on the regenerator.

An obvious crack was also found at the gasket sealings, as shown in Figure A2. This indicates that the gasket sealings has failed and the working gas are able to leak out of the TA Core, resulting in the low sound pressure produced by the DEMO 2 Engine.



Figure A2: Crack on the gasket sealings.

Furthermore, Figure A3 illustrates the appearance of the HHX before and after the rectifications work were carried out. Initially, the convoluted plate was placed in a Lower Housing and sealed off with gasket materials. Due to the failure of the gasket material, a flange was welded to the convoluted plate instead. Holes are drilled at the flange for it to be fastened to the Upper Housing. Besides that, a thick layer of sealant was used in the old design. This reduces the available area for the acoustic air to pass through. In comparison, the welded flange design eliminates the need of the thick layer of gasket sealant, hence increasing the available area for the acoustic air. In addition,

the position of the convoluted plate was welded to the flange such that it is shifted downwards. Therefore, the distance of the plate to the edge of the flange, F , was increased for the top part and decreased for the bottom part. This is to allow a larger cross section at the interface between the HHX and the TBV.

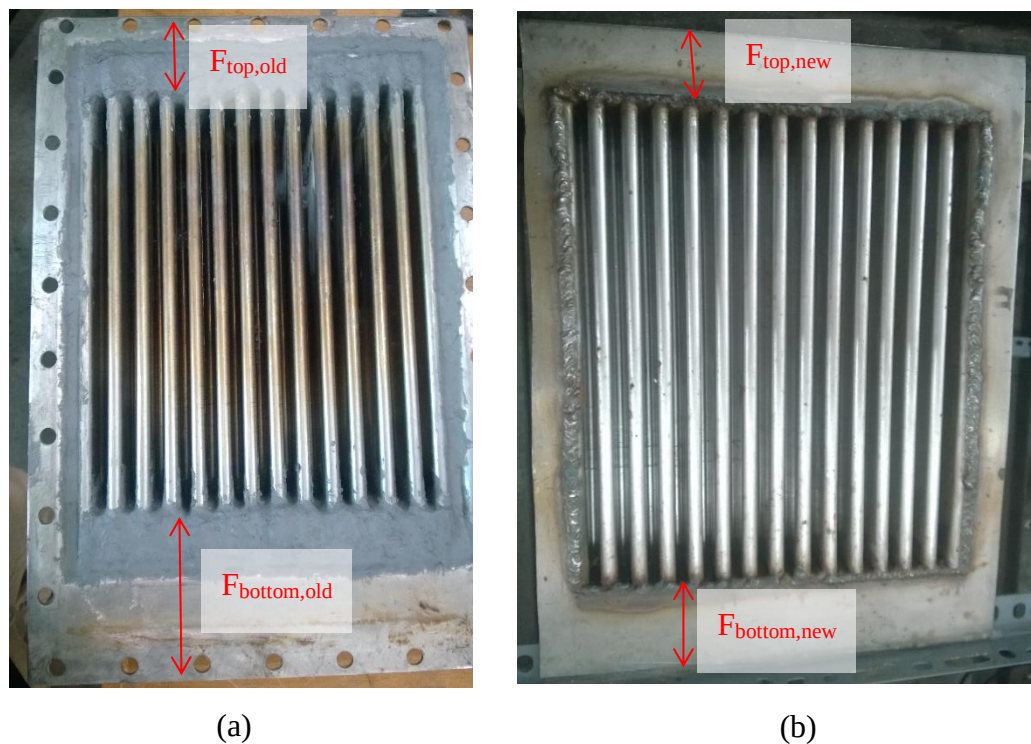


Figure A3: Appearance of HHX (a) before and (b) after the rectification work.

Comparison of the larger cross section available for the acoustic wave to pass through from the HHX to the TBV is depicted in Figure A4. A larger portion of the convoluted plate is visible from the Feedback Pipe connection.



Figure A4: Appearance of the interface between the HHX and the TBV (a) before and (b) after the rectification work.

B. Burst pressure testing of Feedback Loop mounting

Referring to Figure B1, testing of the Pressure Sensors' mounting strength against the pressure in the pipes was performed. The mountings were able to withstand up to 10 kPa of pressure in the pipe. This is more than 7 times above the maximum pressure of the sound wave produced by the DEMO 2 Engine. Therefore, the Pressure Sensor mountings are suitable for the experiments.



Figure B1: Pressure sensor mountings on the Feedback Loop.