EVALUATION OF HEAT EXCHANGER ON THERMOACOUSTIC PERFORMANCE

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ABSTRACT

Thermoacoustic devices have the potential to provide electricity from waste heat to more efficiently use energy resources and to provide new access to electricity for millions of persons around the world. There are many factor influence thermoacoustic performance and this study was focused on a new design of thermoacoustic's heat exchanger and evaluation of its performance in terms of thermal analysis. Through several ideas from researchers in this field, this study was produced with three designs of heat exchangers which are wiretype, fingertype and startype that specifically one of them will be used in experimental test later. Theoretical analysis shows that heat conduction through a full body of heat exchanger are 67.36 W and 39.81 W for both copper and aluminium. Analyzing heat conduction of a fin separately by types of heat exchangers, the highest value of heat conduction through a fin was recorded by startype heat exchanger's fin using copper as material which is 32.84 W. By using ANSYS-CFX software, the heat exchanger's designs were simulated with two thermal conditions which are steady state conduction and transient conduction by substituting material between copper and aluminium to see the engagement between theoretical analysis and numerical analysis. There are three inlet temperatures that are assumed will be supplied by constant waste heat which are 200°C, 350°C and 500°C. The simulation on both steady state and transient condition found the copper is better in thermal or heat conductor than aluminium due to high value of thermal conductivity, *k*. In terms of design, startype heat exchanger recorded the fastest time to distribute temperature compared to wiretype and fingertype heat exchanger. As a conclusion, the combination between startype design and copper material will produce the best heat exchanger that will be used in experimental test of thermoacoustic system.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

ABSTRAK

Sistem termoakustik berpotensi menyediakan bekalan elektrik daripada haba buangan dalam menggunakan sumber tenaga dengan lebih cekap dan menyediakan akses kepada bekalan elektrik baru untuk berjuta-juta orang di seluruh dunia. Terdapat banyak faktor yang mempengaruhi prestasi termoakustik dan kajian ini telah memberi tumpuan kepada reka bentuk baru penukar haba termoakustik dan penilaian prestasi dari segi analisis terma. Melalui beberapa idea daripada penyelidik dalam bidang ini, kajian ini menghasilkan tiga reka bentuk penukar haba iaitu wiretype, fingertype dan startype di mana salah satu daripadanya akan digunakan dalam uji kaji selepas ini. Analisis teori menunjukkan bahawa pengaliran haba melalui keseluruhan jasad penukar haba adalah 67.36 W dan 39.81 W masing-masing bagi tembaga dan aluminium. Menganalisis pengaliran haba sirip secara berasingan mengikut jenis penukar haba, nilai tertinggi pengaliran haba melalui sirip dicatatkan oleh sirip penukar haba startype dengan menggunakan tembaga sebagai bahan dengan nilai pengaliran haba adalah 32.84 W. Dengan menggunakan perisian ANSYS-CFX, reka bentuk penukar haba ini disimulasikan dengan dua keadaan iaitu pengaliran haba keadaan mantap dan pengaliran haba sementara dengan menggantikan di antara tembaga dan aluminium untuk melihat perkaitan di antara analisis teori dan analisis berangka. Terdapat tiga suhu masuk yang diandaikan akan dibekalkan oleh haba buangan secara berterusan iaitu 200°C, 350°C dan 500°C. Simulasi di dalam kedua-dua keadaanmantap dan fana mendapati tembaga sebagai konduktor haba yang lebih baik daripada aluminium kerana nilai keberaliran haba, *k* yang tinggi. Dari segi reka bentuk, penukar haba startype mencatatkan masa terpantas untuk menyebarkan suhu berbanding penukar haba wiretype dan fingertype.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Kesimpulannya, gabungan antara reka bentuk startype dan bahan tembaga akan menghasilkan penukar haba terbaik yang akan digunakan dalam uji kaji sistem termoakustik.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

TABLE OF CONTENTS

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF FIGURES

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays, the destruction of the ozone layer by chlorofluorocarbons (CFCs) is increasing at an alarming rate. Generally CFCs are used in various applications, such as plastic insulation for building and appliance, solvent for cleaning and as refrigerants in domestic and industrial refrigeration and air conditioning. In the last two decades, international regulations have been set to ultimately diminish the use of CFCs by developing alternative method that are environmentally benign.Lately,the enhanced use of renewable energies has become a major concern for the world energy policy to meet the target of sustainable development and focusing on decrease of global warming. One of green technology known as thermoacoustic technology can play a significant role in this context because of its advantages over conventional technologies. Thermoacoustic engines are sound-heat energy conversion devices which operate with no moving components, use no-polluting working gases, can be powered by low-grade energetic inputs (waste heat, solar energy,etc.) and join with simple/reliable construction to low fabrication costs (Ishikawa, 1999).

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

1.2 Heat Exchanger

Heat exchangers for thermoacoustic devices are different from traditional ones in several key features. First of all, heat transfer in the thermoacoustic working fluid takes place in oscillating flow characterized by zero mean and very low instantaneous velocity, characterized by a tidal displacement (TD) of the order of several millimeters. Convective heat transfer coefficients on the surfaces of the heat exchangers, essential parameters in heat exchanger design, cannot be predicted for oscillating flow based on methods for unidirectional flows because of the very complex features of oscillating flow and geometries. Experimental data regarding convective heat transfer coefficients are available for a few special conditions and combinations of parameters only (Ishikawa, 1999). Furthermore, the heat exchanger performance depends on numerous geometrical, thermophysical and operational parameters (dependent on the oscillation frequency). Therefore, conventional heat exchanger design methods, such as the logarithmic mean temperature difference (LMTD) or the effectiveness-number of transfer units (e-NTU) method, cannot be applied directly to the design and sizing of heat exchangers for thermoacoustic devices (Cila Herman and Yuwen Chen, 2006)

In order to be fully exploitable on thermoacoustic effect in power production/refrigeration applications, the stack must work in conjunction with a couple of heat exchangers which transfer heat between its edges and external heat sources and sinks. These components have recently been the object of many research studies since a significant improvement of the overall engine's performance is expected to derive from their optimization. The finned-tube (K. Tang*et al.*, 2007), and shell and tube heat exchangers configurations (M.E.H. Tijani and S. Spoelstra, 2008), are commonly used but reliable and univocal design criteria are still lacking. The main goal in designing efficient heat exchangers is the achievementof high transfer rates in conjunction to low acoustic dissipation.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

1.3 Problem Statement

Despite all the developments in thermoacoustic engines, there are still many remaining problems to be investigated in order to increase better prediction on the performance and design of thermoacoustic engines. Particularly lacking is overall research into heat exchangers, and as a consequence heat exchanger in thermoacoustic engine do not have an established method of design. Heat exchangers in thermoacoustic engines are crucial for engines to be utilized in any future application. Furthermore, it is important to make the heat exchange process in heat exchangers efficient to improve the overall efficiency of the thermoacoustic device or system**.** (Ishikawa, 1999)

1.4 Objective Of Project

1. To create a new designs of heat exchanger of thermoacoustic system.
2. To evaluate the design of heat exchanger on thermoacoustic performance (thermal analysis).
3. To proposed the best heat exchanger's design to be fabricated for experimental purpose.

1.5 Scope of the Project

1. To do CAD design with any of CAD tools such as Pro-E, AUTODESK Inventor, UG etc. based on conceptual design.
2. To do theoretical analysis (calculation) due to CAD design.
3. To do numerical analysis/simulation of thermoacoustic heat exchanger by using ANSYS-CFX (Thermal Analysis)

1.6 Contribution of This Project

As a result, I expect that the numerical/simulation data on thermal analysis will be gained by ANSYS-CFX analysis will get a very good agreement with theoretical

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

data/result that will be obtained earlier through calculation. As a conclusion, the best design of heat exchanger will show the most effective temperature distribution in engagement of theoretical analysis (heat conduction) with ANSYS-CFX simulation as well as the best material in conducting heat. If that so, the overall heat exchanger efficiency will be increased together with increasing the overall efficiency of the thermoacoustic device or system.

1.7 Report Outline

In this report, the literature study about the thermoacoustic principle, heat exchangers, design of thermoacoustic heat exchangers, heat transfer and performance of thermoacoustic as well as numerical analysis are given in Chapter 2. Chapter 3 provides the theoretical background of the overall project methodology which is represent in a flowchart. The detail procedures of ANSYS-CFX analysis to do thermal analysis in thermoacoustic heat exchanger are elaborated in Chapter 3. The simulation analysis of temperature distribution in thermoacoustic heat exchanger will be discussed in chapter 4 by relating to the theoretical studies at the first of the chapter. The results obtained from the analysis among three suggested heat exchanger's design, and the discussion of possible reasons for the particular trends will be observed. In the last chapter, conclusions and suggestions for future work will be listed and elaborated.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Thermoacoustic is a branch of science dealing with the conversion of heat energy into sound energy and vice versa. Device that converts heat energy into sound or acoustic work is called thermoacoustic heat engine or prime mover and the device that transfers heat from a low temperature reservoir to a high temperature reservoir by utilizing sound or acoustic work is called thermoacoustic refrigerator. Although the thermoacoustic phenomenon was discovered more than a century ago, the rapid advancement in this field occurred during the past three decades when the theoretical understanding of the phenomenon was developed along with the prototype devices based on this technology (MazenA.Eldeeb et al., 2011).

The thermoacoustic technology has not reached the technical maturity yet, as a result, the performance of thermoacoustic devices is still lower than their convectional counterparts. Thus, significant efforts are needed to bring this technology to maturity and develop competitive thermoacoustic devices. There are several advantages of heat engines and refrigerators based on thermoacoustic technology as compared to the conventional ones. These devices have fewer components with at most one moving component with no sliding sealsand no harmful refrigerants or chemicals are required. Air or any inert gas can be used as working fluids which are environmentallyfriendly. Furthermore, the fabrication and maintenance costs are low due to inherent simplicity of the thermoacoustic devices low due to inherent simplicity of the thermoacoustic devices.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

2.2 Thermoacoustic Engines/Devices/Systems

Thermoacoustics is a relatively new topic in science and engineering. Only few devices exist to date, and these are mostly for research purposes. The first thermoacoustic device was the Sondhauss tube. **Figure 2.1** shows illustrations of a Sondhauss tube. Sondhauss quantitatively investigated the relation between the pitch of the sound and the dimensions of the device.

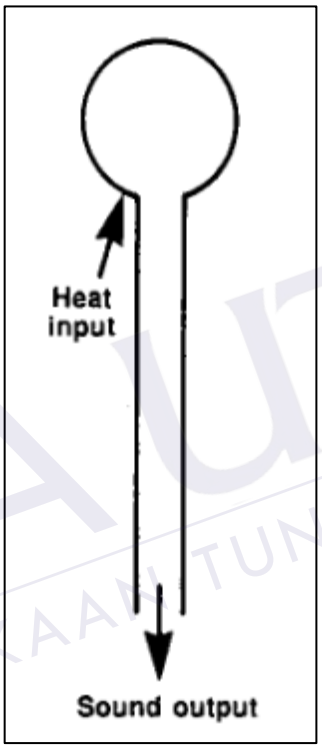

Figure 2.1: Illustration of the Sondhauss tube (Swift G.W., 1988)

In almost all cases where heat is communicated to a body expansion ensues, and this expansion may be made to do mechanical work. If the phases of the forces thus operative be favorable, a vibration may be maintained. For the sake of simplicity, a tube, hot at the closed end getting gradually cooler towards the open end, may be considered. At a quarter of a period before the phase of the greatest condensation, the air is moving inwards, i.e., towards the closed end, and therefore is passing from colder to hotter parts of the tube, but in fact the adjustment of temperature takes time, and thus the temperature of the air deviates from that of the neighboring parts of the tube, inclining

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

towards the temperature of that part of the tube from which the air has just come. From this it follows that at the phase of greatest condensation heat is received by the air, and at the phase of greatest rarefaction heat is given up from it, and thus there is a tendency to maintain the vibrations.

Thermoacoustic devices can be divided into two classes, standing-wave and travelling-wave devices. Travelling-wave devices can be described with the Stirling thermodynamic cycle, and standing-wave devices with the Brayton cycle. These two classes of thermoacoustics devices can again be divided in two thermodynamic types of engines, a prime mover (or simply heat engine), and a heat pump. The prime mover creates work using heat and a heat pump creates or moves heat using work. A thermoacoustic device basically consists of heat exchangers, a resonator, and a stack or regenerator.With standing-wave devices this part is called a stack, and with travelling-wave devices this part is the regenerator. A half wavelength (or a quarter wavelength) acoustic standing wave is generated in the resonator. The thermoacoustic phenomenon takes place in the stack when a nonzero temperature gradient imposed along the stack plates (i.e. parallel to the direction of the sound wave propagation) interacts with the sound wave oscillations. The heat exchangers are responsible of transferring heat in and out of a thermoacoustic device at their desired temperatures, thus maintaining a given temperature gradient along the stack.

2.3 Heat exchangers

Heat exchangers are used to transfer heat into or out of a system. There are many different types of heat exchangers for all kinds of applications, but heat exchangers for thermoacoustic devices are not yet commonly available. The fundamental design challenge is to provide good thermal contact between the flows while causing a minimal pressure drop. The heat exchangers for thermoacoustic devices should have good thermal conductivity and enough area to transfer heat. Like with a stack, the blockage ratio is also important for heat exchangers since the sound waves should be perturbed as little as possible.According to Swift G.W, (1988), the length of a heat exchanger, (L_{hx})

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

should be around twice the displacement amplitude, (ξ_{osc}) and can be calculated by following formula;

$$\mathbf{L_{hx} = 2.\xi_{osc} = 2.U_{osc}/\omega} \quad (2.1)$$

Where L_{hx} this is the length over which a particle can move. Here, (u) is the x-component of the velocity, (ω) is the enthalpy per unit mass.

2.4 Design of Thermoacoustic Heat Exchanger

As stated by Henrik Johansson (2007), the use of the heat exchangers is to supply heat at the cold side of the stack while extracting the heat from the hot side of the stack. The suitable design of the heat exchanger is very important in order to make sure that it can extract the heat from the system. Not just that, it is also important to make sure that the design should make a good thermal contact between two flowing systems, but with a very minimal pressure drop in both stream. He also mentioned that the heat pumping mechanism involved the gas parcel at the end of the stack which is at the end of the chain of gas parcels. The optimal length of the heat exchangers corresponded to twice the particle displacement amplitude as the gas parcels oscillate back and forth between the stack and the heat exchanger as shown is **Figure 2.2**.

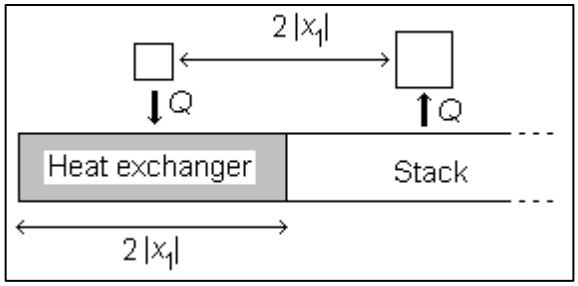

Figure 2.2: An illustration of the optimal length of the heat exchanger corresponding to twice the peak displacement amplitude of the oscillating particles (Henrik Johansson , 2007)

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

Figure 2.3 showed the picture of the heat exchangers which was designed by Henrik Johansson (2007). It was made of 6mm copper tube and it was then wound into spiral with about 18mm spacing. The spacing was chosen to have a block ratio close to the block ratio of the stack. By using equation 3.19, it was calculated to B = 0.75. The water was circulated in tube to supply and extract the heat exchangers. He also added that, two water pumps were required to circulate and control the velocity of the water, one for each heat exchanger. He suggested that the heat exchangers can be optimized by increasing the area and length. To increase the area, he suggested to add more rotations in the spiral construction, use a thinner copper tube and examine and optimize the volume flow rate of the water.

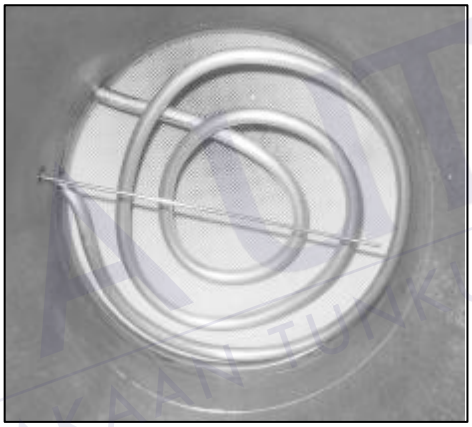

Figure 2.3: The picture shows the heat exchanger and the thermometer on the hot side of the stack (Henrik Johansson , 2007)

However, not many researchers had done research on designing the two end of the stack (Masoud Akhavanbazaz*et al.*, 2004). He believed that the proper design of the heat exchangers were very important for the overall performance of the refrigerator. It was because, due to poor design, it could block the gas particles from entering and leaving the stack and it would definitely affect the device performances. He agreed that by designing good heat exchangers, it could minimize the heat exchange between the heat exchanger fluids and the stack and at the same time it could minimize the blockage of the gas particles.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

Eventhough Masoud Akhavanbazaz *et al.* (2004) said that not many researchers had done research in designing the heat exchanger, there were researchers who were committedly design the heat exchangers. For example, Meghan Labounty and Andrew Lingenfelter (2008). They had proposed to make a heat exchanger out of copper mesh. They proposed Tijani's design where they wound together two copper sheets to construct a heat exchanger. One of the cooper sheets would have a sine channel structure produced by passing the copper sheet through a toothed device and the other one would be flat. Before wind the two copper sheets around one another at one end, at first they will be soldered together at the other end. The two sheets would be soldered to the external surface of the spiral once they completely rolled up. The design is as shown in **Figure 2.4**.

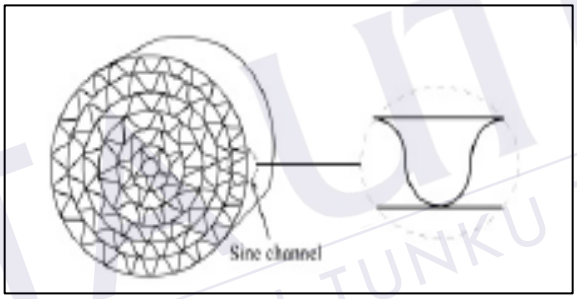

Figure 2.4: Proposed Heat Exchanger Design by Meghan Labounty and Andrew Lingenfelter (2008)

At first, they had chosen aluminium sheeting for the heat exchanger design because it was the next best option based on its availability and price, eventhough they believed on the fact that cooper sheeting is much more thermally conductive than aluminium. However, after analising Tijani's design and due to limitation of time and the expertise, the had chosen copper mesh and copper wool that were available in the laboratory. Ten circles were cut out of the sheet of copper mesh in order to make heat exchange. In order to ensure proper thermal contact between the stack and the heat exchanger, each heat exchanger would be composed of five circles stacked together, varying in size from 4.56 to 4.81 cm. **Figure 2.5** shows the cooper mesh inside of the threads of copper adapter before being screwed onto the stack.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

Figure 2.5: Copper Mesh Heat Exchanger (Meghan Labounty and Andrew Lingenfelter, 2008)

Apart from Tijani's design by Meghan Labounty and Andrew Lingenfelter (2008), there were other researchers which were Cila Herman and Yuwen Chan (2006) that proposed three designs of heat exchangers suitable for thermoacoustic refrigerators, parallel-strips, finned-tubes and flat-tube-banks heat exchangers as in **Figure 2.6**. It shows the heat exchanger together with the corresponding portion of the stack plate, viewed perpendicular to the plane of stack plate. They also added that the base will be maintained at a temperature different from the thermoacoustic working fluid. Heat conduction from the middle (resonance tube axis) to the ends of the highly conductive metal strips will rely on the transport of thermal energy in the parallel-strips heat exchanger as shown in **Figure 2.6a**. The metal strips of the heat exchanger should ideally be aligned with the plates when the stack plates are parallel. However, they added that, eventhough the blockage of acoustic waves caused by the heat exchanger strips in the resonance tube is minimized and acoustic losses are reduced, but the thermal resistance of the heat exchanger strips in this solution is large, because of the heat transfer relying on heat conduction alone along the strips. However, Garrett et al. (1994) suggested that this design was suitable for small thermoacoustic refrigerators with cooling loads under 10 W.

Holfer (1993) had designed and built the parallel-strips heat exchanger attached to a spirally wound stack, as shown in **Figure 2.6d**. Instead of using parallel stack plates, he used a long plastic sheet wound spirally around a plastic rod and spaced. He used copper as the heat exchanger strips. Swift (1988) then added that the width (in the

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

direction of the acoustic axis) of the heat exchangers corresponds to the TD, since this allows the gas parcels to be in contact both with the stack plate and the heat exchangers, as illustrated in **Figure 2.6e** and **2.6f**. The heat picked up from the heat exchanger by the gas parcel would be delivered (returned) to the same heat exchanger (hot heat exchanger in **Figure 2.6e**, dashed lines), making the portion of the heat exchanger inefficient in the energy migration process if the heat exchangers were longer than the tidal displacement. On the other hand, the gas parcel would also move beyond the heat exchanger strip if they were shorter than the tidal displacement, and the heat from the heat exchangers (cold heat exchanger in **Figure 2.6f**, dashed line) could not be delivered to or extracted. The amount of the heat that had to be rejected to the environment controlled the design choices in Hofler's solution. The cold heat exchanger was larger since the hot heat exchanger had to transport more heat. He also added that the heat transfer rates of the order of a few watts for these heat exchangers. Sealing problems are avoided and the mechanical design can be maintained relatively simple by having this design since it does not require a transport fluid being pumped and delivered into the resonance tube. However, flow blockage occurred due to the mismatch between the stack and heat exchanger geometries (**Figure 2.6d**).

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

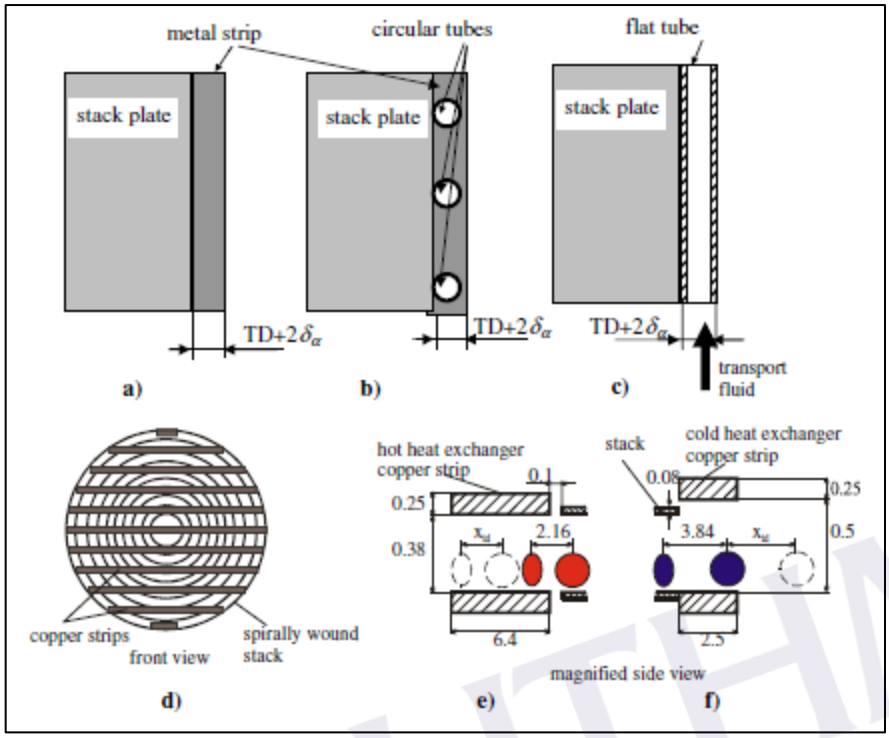

Figure 2.6: Schematic of three heat exchangers designs for thermoacoustic refrigerators: a) parallel-strips heat exchanger, b) heat exchanger with finned tubes and c) flat tube banks. d) Design of Hofler's heat exchanger (Hofler, 1993), cross section of the e) hot and f) cold heat exchangers (all dimensions are in millimeters)(Cila Herman and Yuwen Chan, 2006)

Not only Holfer (1993), W.Dai *et. al.* (2004) also proposed improvement in the heat exchangers in the thermoacoustic systems. They stated that the pressure ratios of 1.15/Helium and 1.22/Nitrogen can be obtained on a ¼ wavelength standing wave system by using Electrical Discharge Machining (EDM) cut heat exchangers which was used in manufacturing the heat exchangers for both the hot-end heat exchanger and the water-cooled heat exchanger. **Figure 2.7** shows a photo of a representative water-cooled heat exchanger. Water will flow through the side grooves and holes. The gas passage consists of many narrow channels surrounded by copper fins formed by the EDM process. Without any soldering work, this design ensures heat exchanger integrity. The hot-end heat exchanger uses a similar design. They also added that three sheathed K-type thermocouples have been placed at the hot-end heat exchanger exit, inside the hot-end heat exchanger block, and in the water-cooled heat exchanger exit were used in

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

monitoring the performance of this design. They claimed that these heat exchangers perform quite well as seen in **Figure 2.8**. The temperature difference between the gas and the copper block could be kept around 10K, even with a heating power of 1.8 kW, when they used helium as the working gas. They however added that, the exit of the water cooled heat exchanger's gas temperature could be kept around 15°C above the water temperature.

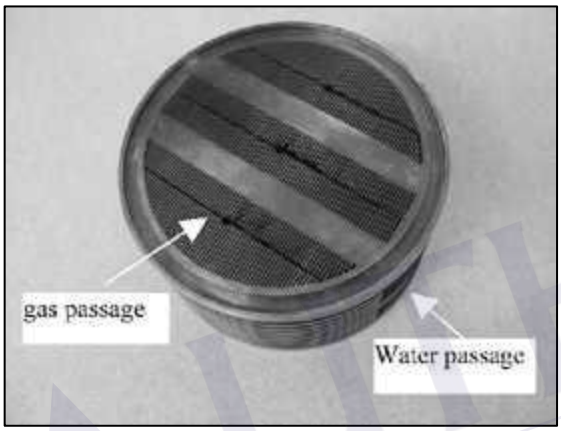

Figure 2.7: Photo of EDM-cut water cooled heat exchanger(W.Dai *et. al.*, 2004)

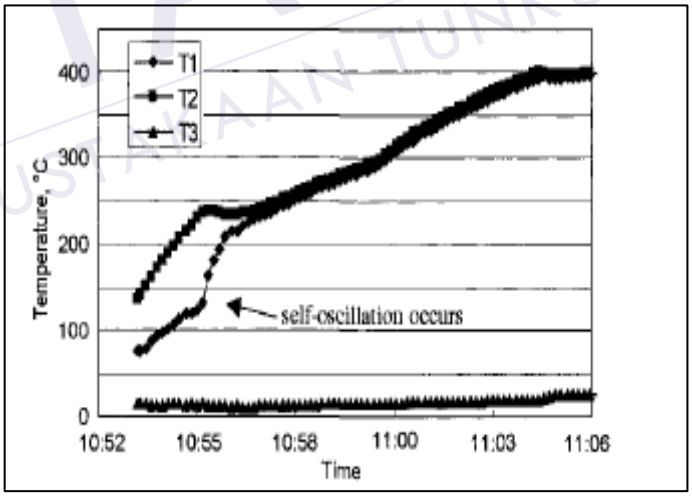

Figure 2.8: Temperature history of the three thermocouples (W.Dai *et. al.*, 2004)

When W.Dai *et al.* (2004) improved the heat exchangers in the thermoacoustic systems, M.E.H. Tijani ***et al.*** (2001) before that discussed about the design procedure of a thermoacoustic refrigerator. They used the approximate short-stack and boundary-layer expressions for acoustic power and heat flow. They showed that by using

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

dimensionless parameters and making choices of some parameters, the great number of parameters can be reduced. In the research, they had discusses the optimization of the different parts of the thermoacoustic refrigerator. They also presented about the manufacturing procedure of a thermoacoustic refrigerator in 2001. They described in detail the construction of the different parts of the refrigerator. They had assembled the system and measured the first performance. They showed that the measurements showed that the system behaves very well as expected. They had achieved a low temperature of -65°C. The effect of someimportant thermoacoustic parameters, such as the Prandtl number using binary gas mixtures, and the stack plate spacing was studied by using the thermoacoustic refrigerator.

After W.Dai *et al*. (2004) improved the heat exchangers in the thermoacoustic systems, Hadi Babaei and Kamran Siddiqui (2008) after that studied a comprehensive design and optimization algorithm in designing thermoacoustic devices. They stated that the present algorithm which was based on the simplified linear thermoacoustic model was able to design thermoacoustically-driven thermoacoustic refrigerators that can serve as sustainable refrigeration systems. In addition, they also included new features based on the energy balance to design individual thermoacoustic engines and acoustically-driven thermoacoustic refrigerators. The algorithm was also included different correlations based on the energy balance for different device configurations. They also implemented the entropy balance on the device to refine the optimization process. The thermoacoustically-driven thermoacoustic refrigerator was designed and optimized to demonstrate the working of the algorithm. Before that they had described a step-by-step design and optimization procedure which was followed by a case study. They declared that the results from the algorithm were in good agreement which was obtained from the computer code DeltaE.

2.5 Heat Transfer in Thermoacoustic System

After discussing about what does it mean by heat exchanger and the design of Thermoacoustic Heat Exchanger (THEx), now let’s take a look at heat transfer in

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

thermoacoustic engines. Artur J. Jaworski and A. Piccolo (2012) addressed the issues of heat transfer in oscillatory flow conditions, which were typically found in thermoacoustic devices. A mixture of experimental and numerical approaches was used in analysing the processes in the individual "channels" of the parallel-plate heat exchangers (HX). They also described the design of experimental apparatus to study the thermal-fluid processes controlling heat transfer in thermoacoustic heat exchangers on the microscale of the individual channels. The Planar Laser Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV) techniques were applied to obtain spatially and temporally resolved temperature and velocity fields within the HX channels. The temperature fields allowed obtaining the local and global, phase dependent heat transfer rates and Nusselt numbers, and their dependence on the Reynolds number of the oscillating flow.

In the numerical part, Artur J. Jaworski and A. Piccolo (2012) dealed with the implementation of CFD modeling capabilities to capture the physics of thermal-fluid processes in the micro-scale and to validate the models against the experimental data. They had implemented a two-dimensional low Mach number computational model to analyse the time-averaged temperature field and heat transfer rates in a representative domain of the HXs. Based on the energy balance, these were derived by integrating the thermoacoustic equations of the standard linear theory into a numerical calculus scheme. They suggested that the optimal performance of heat exchangers can be achieved when the gas displacement amplitude is close to the length of hot and cold heat exchanger. They added that the heat transfer coefficients from the gas-side can be predicted with a confidence of about 40% at moderate acoustic Reynolds numbers.

In the previous year (A. Piccolo, 2011), he presented in his research a simplified computational method for studying the heat transfer characteristics of parallel plate thermoacoustic heat exchangers. The model integrated the thermoacoustic equations of the standard linear theory into an energy balance-based numerical calculus scheme. He gave details of the time-averaged temperature and heat flux density distributions within a representative domain of the heat exchangers and adjoining stack. He also investigated

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

the effect of operation conditions and geometrical parameters on the heat exchanger performance. The main conclusions for HX design were drawn as far as fin length, fin spacing, blockage ratio, gas and secondary fluid-side heat transfer coefficients were concerned. He also found that the most relevant fact was that the fin length and spacing affected in conjunction the heat exchanger behavior and in order to minimize thermal losses localized at the HX-stack junctions, it had to be simultaneously optimized. He finally claimed that the model predictions fit experimental data found in literature within 36% and 49% were respectively at moderate and high acoustic Reynolds numbers.

There were some important factors that influenced the heat transfer and construction of the system were identified by Emmanuel C. Nsofor *et al.* (2007). He presented an experimental investigations on the oscillatory flow heat transfer at the heat exchanger of the thermoacoustic refrigeration system. An empirical correlation for this heat transfer was developed. This study confirmed some previous studies which showed that using straight flow correlations for the analysis and design of system could result in significant errors. He stated that the marked difference was from the fact that compared to straight flows, the nature of oscillatory flows was not allow fluid particles close to the solid surface to make as much contact with the heat exchanger surface as the particles in straight flows. The results also showed the relationship between the oscillatory heat transfer coefficient at the heat exchangers, the mean pressure and oscillation frequency. Higher mean pressures result in greater heat transfer coefficients if the thermoacoustic refrigerating system operates at the corresponding resonant frequency. However, to accommodate stack fabrication, a compromise had to be reached.

A simplified model of heat transfer was developed to investigate the thermal behavior of heat exchangers and stack plates of thermoacoustic devices by Cila Herman and Yuwen Chan (2006). The model took advantage of previous results describing the thermal behavior of the thermoacoustic core and heat transfer in oscillating flow to study the performance of heat exchangers attached to the core. The configuration considered was a flat tube (with a working fluid flowing in the tube) of the thickness of the stack plate attached to both ends of the stack plate. They had organized transport fluids in the

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

heat exchangers, stack plate, geometrical and operational parameters and the thermoacoustic working fluid as well as thermophysical properties of the heat exchangers into dimensionless groups that allowed accounting for their impact on the performance of the heat exchangers. Two types of thermal boundary conditions which were constant temperature and constant heat flux along the heat exchanger tubes were considered. They also carried out numerical simulations with the model that introduced in their paper. The temperature distributions and heat fluxes near the edge of the stack plate were found to be nonlinear. Not only that, they also analyzed the influence of system parameters on the thermal performance of the heat exchangers.

2.6 Performance in ThermoacousticSystems

N.M. Hariharan *et al.* (2012) presented the theoretical and experimental investigations to examine the influence of plate thickness (PT), plate spacing (PS), and resonator length with constant stacked length on the performance of standing wave open end thermoacoustic primemover. In order to observe the system performance in terms of onset temperature difference frequency, and pressure amplitude, experiments were conducted. He stated that the results showed that the PT of 0.3 mm yielded a large onset temperature difference to generate oscillations when compared to 0.5 mm plates irrespective of PS. The working frequency was decreased and onset temperature difference and pressure amplitude for both 0.3 and 0.5 mm thick plates were increased after the increase of PS and resonator length. They also agreed that the normalized acoustic power generated from the 0.3 mm PS was higher than the 0.5 mm. They said that the acoustic power decreased with the increase in resonator length and decrease in plate thickness. According to them, 230–250 Hz frequency of acoustic waves was generated, which may be adequate to drive a thermoacoustic refrigerator in the present system. It was concluded that the theoretical results obtained from DeltaEc were in good agreement with the experimental results.

As N.M. Hariharan*et al.* (2012) examined the influence of plate thickness (PT), plate spacing (PS), and resonator length with constant stack length on the performance

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

of standing wave open end thermoacoustic primemover, Masoud Akhavanbazaz*et al.* (2007) before that had investigated the impact of the gas blockage for three cases; no heat exchanger, heat exchanger with small thermal contact area and heat exchanger with large thermal contact area. The research found that the gas blockage fraction was different in all cases and had a significant impact on the thermoacoustic process inside the stack. Not only that, he also mentioned that the heat transfer from the cold end of the stack to the hot end decreases with an increase in the gas blockage and the relationship between the gas blockage fraction and the temperature difference across the stack was linear. He also studied the impact of heat exchangers on the thermoacoustic process. The results showed that a heat exchanger with larger thermal contact area increased the heat exchange between the heat exchanger fluid and the stack, but reduced the cooling power and increased the work input to the stack. He then concluded that when thermoacoustic devices were used as a refrigerator, there was a compromise between the cooling power of the device and the heat exchanged with the heat exchangers. Therefore, the optimizations of the parameters were necessary in order to optimize the performance of the thermoacoustic refrigerator.

2.7 Numerical Analysis in Thermoacoustic Systems

Finally in the numerical part of research about heat transfer in oscillatory flow conditions, Artur J. Jaworski and A. Piccolo (2012) dealt with the implementation of CFD modeling capabilities to capture the physics of thermal-fluid processes in the micro-scale and to validate the models against the experimental data. They had implemented a two-dimensional low Mach number computational model to analyze the time-averaged temperature field and heat transfer rates in a representative domain of the HXs. It was derived by integrating the thermoacoustic equations of the standard linear theory into a numerical calculus scheme based on the energy balance. They added that the comparisons between the experimental and numerical results in terms of temperature and heat transfer distributions suggested that when the gas displacement amplitude was close to the length of hot and cold heat exchanger, the optimal performance of heat exchangers could be achieved. He concluded that the heat transfer coefficients from the

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

gas-side could be predicted with a confidence of about 40% at moderate acoustic Reynolds numbers.

Guoyao Yu *et al.* (2010) on the other hand, applied the commercial CFD code FLUENT 6.1 to an experimental 300 Hz standing wave thermoacoustic heat engine. They had made few attempts to accomplish modeling and simulation of the experimental system with almost the same working conditions and parameters. They found out that the porous media model was not suitable for the simulation of the stack. However, a fluid–solid coupled model, which realized the finite heat exchange inside the stack, was appropriate for a successful simulation. The entire evolution process of dynamic pressure, including the steep rise of mean pressure, onset temperature, amplification process and final saturation were clearly observed. In addition, they also demonstrated the unique acoustic and thermal characteristics of the standing wave thermoacoustic heat engine. It was found that through the analysis on the cross-sectional mass flow rate, there was no Gedeon DC flow existing in the standing wave engine, which validated the simulation. Moreover, nonlinear vortex evolution in the ends of the stack andthe gas reservoir of the resonator was shown, demonstrating good agreement with the experiments. They also demonstrated the validity of the CFD simulation by comparing results with the experimental system in terms of the resonant frequency, the onset temperature and the acoustical pressure amplitude, which showed a good agreement. They agreed that the CFD simulation was a very powerful tool to study complicated, nonlinear effects of thermoacoustic systems. However, they stated that the accomplished work was still preliminary, and much effort was still required to fully understand the complex phenomena in the thermoacoustic heat engines. They suggested that further efforts might include studying the validity of turbulence model and directly simulating a 3D experimental system.

There were several researches done to identify an approach to achieve reduction of the footprint. And one of it was a research done by Florian Zink *et al.*(2010). They identified the introduction of curvature to the resonator as one approach to achieve this reduction of the footprint. They had developed a successful simulation of said engine in

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

Fluent (CFD) in order to investigate the effect of curvature on the performance of a thermoacoustic engine. They were able to replicate the thermoacoustic effect through the amplification of pressure waves by using a small pressure disturbance and a driving temperature gradient across the modeled stack as the only energy input. To quantify (qualitatively) the influence of resonator curvature on the engine's ability to sustain strong thermoacoustic oscillations, the model was utilized and moved beyond the investigation of an individual thermoacoustic couple. As a conclusion, they showed that curvature in the resonator influences both the amplitude and the frequency of the sound waves, depending on the severity of curvature. They suggested that both effects must be considered when thermoacoustic refrigerators are designed, because a small change in operating conditions can result in drastic changes in performance.

Florian Zink *et al.* (2010) had demonstrated the extension of previous modeling efforts of a thermoacoustic engine (TAE) to include a cooling stack. Their new model only utilizes thermal energy as an input rather than previous investigations that illustrated thermoacoustic cooling with oscillations imposed as a boundary condition. The oscillations were thus created within the model as part of the simulation. They also stated that from their previous model, the TAE was driven using a temperature gradient imposed along the horizontal stack surfaces. Oscillations were induced with a small initial pressure disturbance. The temperature of the gas was recorded along the cooling stack once thermoacoustic oscillations were achieved. A decrease in temperature below ambient was proven. It was consistent with temperature measurements taken from a similar physical model. They stated that the performance was limited by the design of the TAR, specifically the location of the cooling stack in the direct proximity of the driving stack towards the open end of the modeled k/4 resonator. While providing comparatively small pressure amplitude and viscous losses, according to them the location was responsible for relatively high velocities. They believed that the cooling stack closer should be located to the pressure node that should yield better performance. They concluded that their presented model served as advancement in the demonstration of the principle of thermally driven cooling using CFD analysis.

PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Jiangrong Xu *et al.* (2011) on the other hand discussed thermoacoustic refrigeration with method of numerical simulation. At first, the current research situation and conclusion were sum up briefly. Before they finally declared and simulated a thermoacoustic cooler model, they would provide theory model of numerical simulation. physical properties such as temperature, velocity, pressure, density and turbulent intensity, and primarily studied the temporal and spatial variation of parameters were the focus of the research. They had achieved the lowest temperature which was 243K, by treating the heat exchangers and resonator as porous area, with 15atm pressure and 20Hz frequency. Not only that, they also discussed the mechanism of the result, hold the gas at the impact of pressure wave, oscillated back and forth in pulse tube, compressed and expanded repeatedly and also urge the heat in right space to be transmitted outside via exchangers and resonator. According to them, the conclusion was taken as a guiding function for the development of thermoacoustic cooler.

The next year after that, JiangrongXu*et al.* (2012), presented the structural improved thermoacoustic cooler by using *numerical method*. The heat transfer mathematics model of porous medium firstly would be set up. After that, they design an improved shape of thermoacoustic cooler. According to them, later the heat transfer process was simulated roundly, and the detailed analysis focused on the parameters of heat transfer process, such as temperature, velocity, pressure, and density. They concluded that tube external shape changed had an obvious effect on refrigeration effect

One of the researchers groups that discussed about the numerical analysis in the previous years was Cila Herman and Yuwen Chan (2006). In their research in investigation of the thermal behavior of heat exchangers and stack plates of thermoacoustic devices, they had used numerical simulation for their simplified model of heat transfer. They found that the heat fluxes near the edge of the stack plate and temperature distributions to be nonlinear.

Lastly, Gifford and Brandon T. (2012) in their research titled “Analysis of Heat Transfer in a Thermoacoustic Stove using Computational Fluid Dynamics” predicted

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

heat capture and transfer from the biomass fires exhaust gases to the working air inside the unit. The simulation result show that the amount of heat captured was low and therefore it is recommended that design of the hot heat exchanger should be altered to boost heat transfer and results also indicate that radiation is the dominant mode of transferring heat during stove operation is absent of acoustics. Surfaces closest in space and parallel to receiving surfaces had the highest heat flux. Simulations modeling acoustics showed convection during all portions of the sound wave to be greater the mode of heat transfer. Both of them recommended that heat exchanger geometry should be altered to expand the hottest sections of temperature distribution over the hot heat exchanger to improve both radiation at startup and convection during acoustic operation and also conduction in the air should be neglected at all times. Finally, transmission pressure loss simulations for the acoustic wave due to geometry exceed 25%.

As a conclusion, in order to investigate the performance of this new design of thermoacoustic heat exchanger in temperature distribution and heat transfer through numerical analysis/simulation, it is important to review and understands all the previous research on heat exchanger's design, heat transfer, performances and numerical analysis as summarized above that have been done by the researchers in thermoacoustic field.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

CHAPTER 3

METHODOLOGY

3.1 Project Methodology

This chapter provides the theoretical background of the overall project methodology which is represent in a flowchart as illustrated in **Figure 3.1**. The detail procedures of ANSYS-CFX analysis to do thermal analysis in thermoacoustic heat exchanger are also elaborated in this chapter. The results of simulation will be discussed deeply in Chapter 4.

PTTA UTHM PERPUSTAKAAN TUNKU TUN AMINAH

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