وزارة التعليم العالي

والبحث العلــمي

جـــامعة ديالــى

كليـــة الهندســة

قسم الهندسة الميكانيكية

تحقيق تجريبي الثلاجة الحرارية الصوتية ذات الموجة الدائمة مدفوعة بمكبر الصوت العادي

رسالة مقدمة الى

مجلس كلية الهندسة / جامعة ديالى

وهي جزء من متطلبات نيل درجة الماجستير في علوم الهندسة الميكانيكية

من قبل

مهند قيس كامل

اشراف

أ.م.د سامر غازي يحيى

١٤٤٤هـ ٢٠٢٣م

Ministry of Higher Education
and Scientific Research
University of Diyala
College of Engineering
Mechanical Engineering Department

NUMERICAL AND EXPERIMENTAL INVESTIGATION OF STANDING - WAVE THERMOACOUSTIC REFRIGERATOR DRIVEN BY AN ORDINARY LOUDSPEAKER

A Thesis Submitted to the Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in mechanical Engineering

By

Mohanad Qays Kamil

Supervised by

Asst. Prof. Dr. Samir Gh. Yahya

2023A.D **1444A.H**

Chapter One

INTRODUCTION

Chapter One

Introduction

This chapter includes, firstly, basic concepts of Thermoacoustics. Secondly, the motivation behind this research. Thirdly, the aim and objectives of this study. Finally, a brief description of the outline of this thesis.

1.1 Thermoacoustic phenomenon

Thermoacoustics is a branch of science that studies the interactions of two fields: Thermodynamics and Acoustics. This science deals with the conversion of thermal energy to acoustic energy and vice versa. Thermodynamics (thermal energy) is concerned with energy conversion, heat transfer, and efficiency, while acoustics (sound waves) deals with the dynamic properties of working gas oscillations, including gas type, velocity, pressure and phase. Therefore, this type of interference is known as the "thermoacoustic effect". In other words, there is interference between sound waves (pressure and velocity oscillation) and temperature distribution along the stack plates. (G. Swift, 2001; Teja & Kumar, 2017; Tiwatane & Barve, 2014).

Although the thermoacoustic effect was discovered several centuries ago, it did not receive attention as an energy conversion technology. The first phenomenon of sound wave generation was observed in 1777 by Dr. Higgins by placing a hydrogen flame in a glass tube open at both ends in a vertical position (Putnam & Dennis, 1956), which is called “singing flame” (see Figure (1.1a)). Higgins noticed the production of an acoustic wave from the tube and this acoustic oscillation depends on the length and diameter of the tube, in addition to the amount and location of the flame.

(Sondhauss, 1850) conducted another experiment to produce sound through heat. This time using a tube open at one end and closed at the other with a lamp, as shown in Figure (1.1b). It was Discovered that when a flame was placed under a closed bulb, the tube emits oscillations of a specific frequency. wave frequency depends on the length of the tube and the size of the bulb. Sondhauss provided no explanation for the oscillations he observed.

(Rijke, 1859) conducted a study on sound oscillation that was an extension of Higgins' work, but he replaced the supplied heat source (hydrogen flame) for the tube by placing a heated iron grid in the first quadrant of the tube's lower end glass. Note the vibrations of the sound. This tube is called a Rijke tube (see figure 1.1c). He pointed out that when the upper end of the tube is closed, the sound vibration stops and that the convection of the heat flow from heating the air in the tube affects the sound fluctuation.

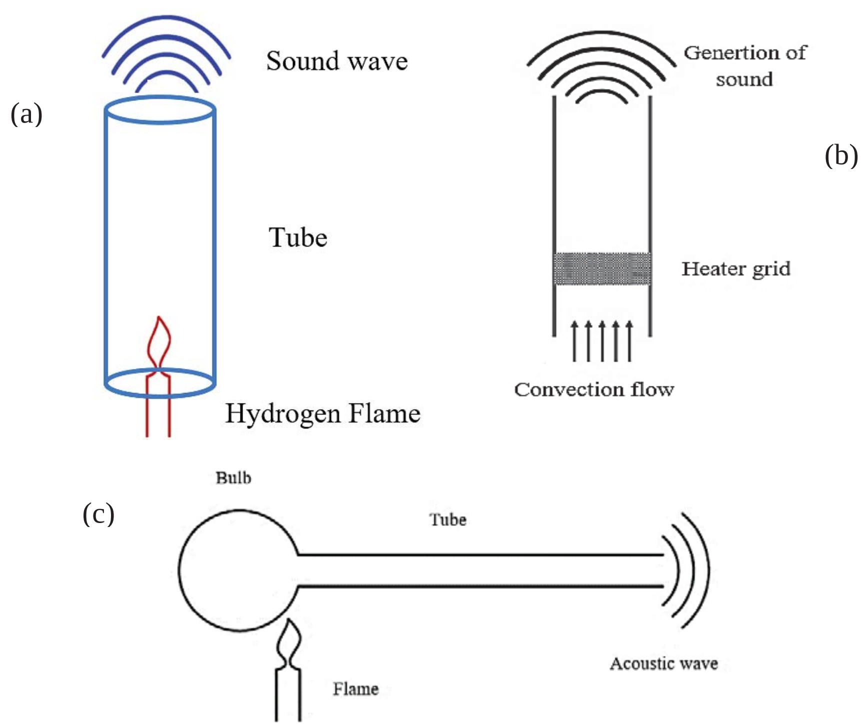

Figure 1.1: Higgins' singing flame (Putnam & Dennis, 1956) (a), Sondhauss's tube (Sondhauss, 1850) (b), The Rijke tube (Rijke, 1859) (c).

After Sondhauss and Rijke failed to explain the phenomenon of acoustic oscillations. In 1896 the British physicist Rayleigh gave an explanation (Rayleigh, 1896), demonstrating that acoustic waves occur when gas (air) expands and contracts. In 1962, Carter et al discovered that the performance of the Sondhauss tube could be improved by placing a porous part called a stack (Collard, 2012), which consists of parallel plates inside the tube, to improve the heat transfer characteristics between the plates and the gas, resulting in a temperature gradient on along of the plates to improve heat transfer efficiency. The stack later became the most important component in the thermoacoustic system. However, there was clear progress in thermoacoustic phenomena, which was by Rott after he presented a series of research papers. (Rott, 1980) presented a paper which explained the interpretation of thermoacoustic phenomena and the solution of linear equations to open the way for other researchers to understand the thermoacoustic effect and build thermoacoustic devices (engines and refrigerators). Since building the first thermoacoustic refrigerator by Hofler in the eighties of the last century (Hofler, 1986), thermoacoustic technology has received increasing attention as a new research area for heat engines and heat pumps. In particular, at Los Elmore National Laboratories in the US, Swift and others were involved in the development of thermoacoustic systems.

The main criterion to identify the type of wave excitation within the system is the phase difference between pressure wave and velocity wave. However, thermoacoustic system operation two modes are standing wave and travelling wave.

Standing wave thermoacoustic is the first type of mode which has the phase difference between pressure and velocity 90°. in other words, there is a phase lag of 90° between pressure and velocity (see figure (1.2a)). As opposed to the standing wave thermoacoustic, the pressure and velocity waves within a traveling wave system will essentially be in phase (Figure 1.2b). This change in pressure/velocity phasing is achieved by introducing a feedback inertance around the regenerator. Because of this more ideal pressure-velocity phasing, the regenerator in a traveling wave system can be designed differently than the stack of a standing wave system (G. Swift, 2001).

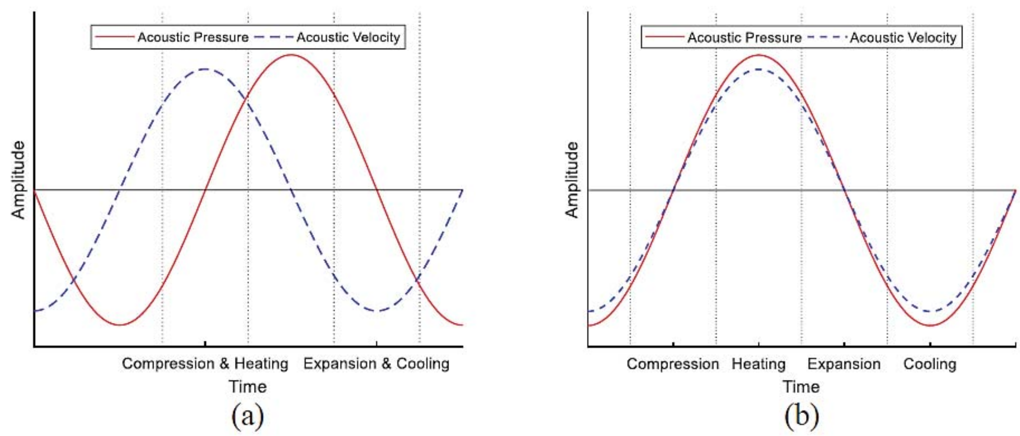

Figure 1.2: Standing-wave (a) and travelling wave (b) thermoacoustic system.

Thermoacoustic researchers classify the thermoacoustic effect into two main categories: the first category is devices that convert thermal energy into acoustic energy, which are called thermoacoustic engines or prime movers. The acoustic waves from thermoacoustic engines are exploited to generate electrical power using an acoustic driver. The second category is devices that convert acoustic energy into thermal energy, which transfers heat from a low-temperature reservoir to a high-temperature reservoir and it is called a thermoacoustic refrigerator or heat pump. Both categories consist of the main components are: stack/ regenerator, heat exchangers and resonator.

Standing-wave thermoacoustic refrigerator simple most commonly, a quarter wavelength resonator. The phase difference between pressure wave and velocity wave results in a compression and displacement within the device. A delay in the heat exchange is required to heat the gas when it is most compressed and reject heat at the point of expansion. For this reason, the thermal penetration depth of the gas (defined as the length across which a sound field interacts thermally within a time of 1/w) is smaller than the flow channels. The irreversibility of the heat transfers in addition to its artificial delay results in a poor performance of the refrigerator. However, the aim of the thesis is improving performance of standing wave thermoacoustic refrigerator.

1.2 Basic Principle of the Thermoacoustic Effect

An acoustic wave consists of oscillations of pressure (i.e., compressions and expansions) and is associated with the oscillatory displacement of the parcels of the medium (working gas) that acoustic waves travel in. Pressure oscillations lead to temperature difference. Thus, the thermoacoustic effect occurs in the stack due to the interaction of the gas parcels with the stack plates. When the gas parcel oscillates inside a stack, it results in a temperature gradient along the plate of the stack. It's also important to note that the temperature gradient along the stack plates plays a great role in determining whether a system functions as an engine (prime mover) or as a refrigerator (heat pump). The condition for an engine is a high-temperature gradient. It's known as the "forward effect" and is related to acoustic wave production from heat. While a small gradient is ideal for a refrigerator (heat pump) that uses acoustic waves to pump heat, this is known as the "reverse effect." It is literally the reverse of the forward effect used in engines. The gradient that separates the two systems is called the critical temperature gradient. For this gradient, the temperature change along the plate matches the temperature change due to adiabatic compression, and no heat flows between the gas parcel and the plate (Jinshah et al., 2013).

The working principle of thermoacoustic refrigerator can be illustrated by taking a tube filled with working gas. It contains a porous part called the stack. It is usually made of a material with low thermal conductivity and it should have a heat capacity greater than the working gas's heat capacity. In addition, its geometry is mostly of parallel plates that the gas parcels oscillate through. It also contains two heat exchangers, which are placed on both sides of the stack (ambient and cold), and which are necessary to transfer certain amounts of heat and maintain the required temperature gradient across the stack, as shown in Figure 1.3a.

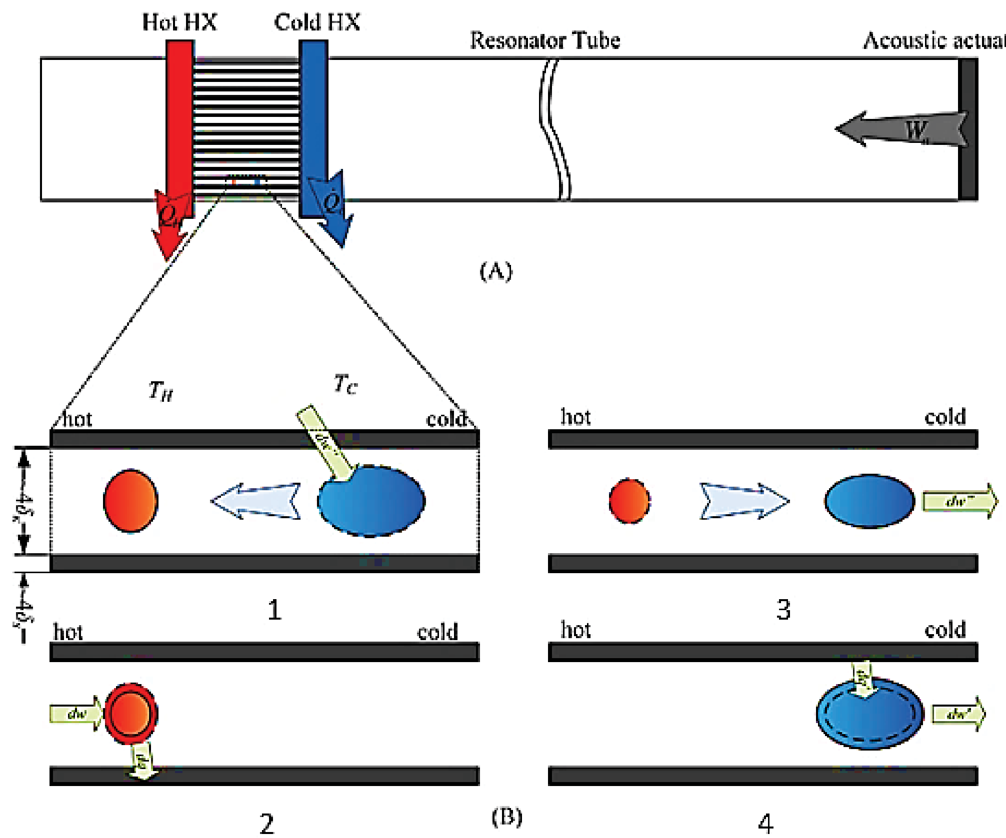

Figure 1.3: Schematic of a simple thermoacoustic refrigerator (a). Working principle of a thermoacoustic refrigerator from the Lagrangian viewpoint (b) (Bansal et al., 2012).

The thermoacoustic process of the refrigeration cycle can be conceptually simplified into four steps. To clarify, the movement of one parcel of the gas can be tracked back and forth and described from the perspective of a Lagrangian (see figure 1.3b). In the first step, the gas parcel undergoes adiabatic compression and travels up the channel due to the acoustic wave. As a result, its pressure increases so the temperature of the parcel increases accordingly. In the meantime, the parcel travels a distance that is twice the acoustic displacement amplitude. Then the second step takes place. When the gas parcel reaches maximum displacement, it will have a higher temperature than the adjacent walls, assuming the imposed temperature gradient is small.

Therefore, the gas parcel undergoes an isobaric process by which it rejects heat to the wall of the stack, resulting in a decrease in the size and temperature of the gas parcel. In the third step, the second half-cycle of the acoustic oscillation moves the parcel back. The gas parcel adiabatically expands as the pressure becomes a minimum, reducing the temperature of the gas. The gas reaches its maximum displacement in the opposite direction with a larger volume and its lowest temperature. Finally, in the step fourth, the parcel's temperature has become lower than the wall temperature (again assuming a small temperature gradient) so that heat flows from the wall to the gas parcel. The process then repeats so that small amounts of heat can be transported up the temperature gradient along the stack plates. To transfer more heat, then adding more channels in parallel will effectively increase the surface area (increasing thermoacoustic effect). Hence, increasing the cooling/heating power of the process. Furthermore, the working gas parameters can be modified so that its temperature fluctuates over a wider range, or the acoustic pressure can be increased to achieve the same effect.

1.3 Motivation Behind the Study of Thermoacoustic Refrigeration Technology

Nowadays, the world is facing many health and environmental problems. One of the causes of these problems is conventional refrigeration techniques. Conventional refrigeration technology (e.g., vapor compression and absorption refrigeration systems) is still dominated and becoming increasingly important in different fields, including industrial, medicinal, gas liquefaction, missiles, ships, and other critical aspects of daily life. Most of conventional refrigeration systems use refrigerants that contain CFCs (chlorofluorocarbons) which are extremely harmful to the ozone layer and can cause global warming issues. As well as, in the event of their leakage, they cause harm to humans. Therefore, new alternatives to conventional refrigeration techniques are required (Alamir & Sidik, 2021; Tartibu, 2016; Zolpakar et al., 2016).

Thermoacoustic refrigeration technology is one of the better options, and it is a relatively new technology with promising future potential because it has many advantages that prompted the choice of this technology (Prashantha et al., 2017; G. Swift, 2001):

- The main advantage of this technology is that it uses inert gases (e.g., helium and argon) or air. These gases are chemically inert, cheap, and commercially available. In addition, non-flammable, non-toxic and do not cause harm to the environment or people in the case of accidental leakage of the working gas. As a result, it is considered friendly to the environment.
- Another significant advantage is that these refrigeration techniques operate with almost no mechanical moving parts, which lead to more reliability, lowering maintenance costs and significantly increasing operational life when compared to conventional refrigeration techniques, which require regular lubrication and the replacement of worn mechanical parts, leading to high maintenance costs.
- This technology has a higher ability to control the cooling load compared to conventional refrigeration technologies. It may be managed using a control system to operate the acoustic driver and reduce electrical power consumption.
- Thermoacoustic refrigerators can be operated by thermoacoustic engines that can utilize thermal energy supplied from any source as input energy

(such as solar energy or the heat of combustion found in the exhaust of gas turbines or other power plants) to the thermoacoustic engine to produce acoustic energy for the thermoacoustic refrigerator (Adeff & Hofler, 2000; Gardner & Howard, 2009). Therefore, it is classified as a renewable energy source.

However, its advantages in mechanical simplicity and environmental and personal safety, as mentioned above, thermoacoustic refrigeration is still unable to compete with conventional technologies due to its have some disadvantages. Among these disadvantages are

- The biggest disadvantage of thermoacoustic refrigeration is their coefficient of performance are lower than the conventional refrigeration where thermoacoustic researchers work to raise its performance.
- Another disadvantage is that these systems are too noisy, but using a proper sound isolation, this disadvantage can be overcome.

This technology is now undergoing theoretical and practical research to mature this technology and build competitive thermoacoustic refrigerators. It may reach a point where it competes with or replaces the rest of the conventional refrigeration systems.

1.4 The Aim and Objectives of the Present Research

This research aim to design and build a standing-wave thermoacoustic refrigerator driven by an ordinary loudspeaker to achieve high cooling power and improve the coefficient of performance (COP). In order to achieve the aim of this research, the current work addresses the following objectives:

1. Designing a standing-wave thermoacoustic refrigerator driven by an ordinary loudspeaker.

2. Simulation the acoustic driver to determine the optimal acoustic conditions (acoustic impedance and its phase) for coupling to the thermoacoustic refrigerator and achieve the best performance in terms of converting electrical energy to acoustic power.
3. Optimizing the simulation of the DELTAEC (Design for Low Amplitude Thermoacoustic Energy Conversion) model to achieve the refrigerator's optimum performance. Also, the impacts of each model parameter (such as the stack, heat exchangers, etc.) on system performance are being shown.
4. To build the standing-wave thermoacoustic refrigerator based on the optimized dimensions obtained from the DeltaEC simulation. The utilization of standard parts available should be considered as far as possible to construct the refrigerator. It is take care to keep the total cost of manufacturing as low as possible.

1.5 Outline of Thesis

- The first chapter is a brief introduction to thermoacoustics, the motivation for the research, and the aim and objectives of the current study.
- The second chapter introduces the important parameters and governing equations of thermoacoustic systems, evaluates their performance, and chooses the working gas for these systems. In addition, it provides a brief overview of electroacoustic transducers and DELTAEC software.
- The third chapter provides an introduction to thermoacoustic devices. In addition, it presents the theoretical models and experimental apparatus for thermoacoustic refrigerators

- The fourth chapter provides evaluates the performance of the loudspeakers available for this project. In addition, it explains the thermoacoustic refrigerator's design and modeling, as well as optimize parameters for each component through simulation using the DeltaEC software to theoretically reach the best performance.
- The fifth chapter explains the experimental refrigerator and its parts, as well as the instruments employed.
- The sixth chapter presents the experimental results and discusses an indication of the effect of operating conditions (such as frequency and mean pressure) and the applied cooling power (cooling load) on the performance of a standing wave thermoacoustic refrigerator.
- The seventh chapter presents conclusions and some recommendations for future work.

Abstract

Thermoacoustic refrigeration technology is one of the best alternatives and most suitable solutions to traditional cooling technologies due to its unique advantages. To improve the use of technology for use in the future, the study concentrates on the design and building of a standing-wave thermoacoustic refrigerator. The thesis explores both theoretical modelling and practical application.

The theoretical includes two parts: the first part deals with simulating and analyzing the loudspeaker and determining its best performance in order to couple with the thermoacoustic refrigerator, while the second part involves designing the thermoacoustic refrigerator using the simulation program DeltaEC. The thermoacoustic refrigerator model is able to achieve a cooling power of about 312 W and a coefficient of performance (COP) of 1.93 at the 25K temperature difference between the ambient and cold heat exchangers.

As for the practical application, it deals with manufacturing and operating the experimental device. where the experimental thermoacoustic refrigerator was set to 0.05 bar of pressure and the loudspeaker was set to 120 Hz. According to the experimental results, the experimental refrigerator achieved a 17.5 °C temperature differential on both sides of the stack without applying a cooling load. When a cooling load is applied, a temperature difference of 6 °C can be achieved between the two ends of the stack at its maximum cooling load of 80 W.