THERMO ACOUSTIC REFRIGERATION SYSTEM FOR USE IN SPACE TECHNOLOGIES

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ABSTRACT:

Thermo acoustic deals with the conversion of heat energy to sound energy or vice versa. Thermo acoustic cooling devices use the thermo acoustic principle to move heat using sound. They consist of a standing wave tube in which a stack of fractional wavelength creates a temperature gradient across the stack, facilitating heat flow. These devices are simple in design and have no harmful effects on the environment. However, their efficiencies are lower than the conventional vapor-compression refrigeration systems. In this study, the design, and development of a Thermo acoustic system for refrigeration application was considered. This study comprised two parts.. In the second parts, the refrigerator was fabricated based on the numerical design. The performance of the device was then tested and analyzed.

The numerical study has shown that the stack length and the position of the stack in the resonator have a significant impact on the overall performance of the thermo acoustic device. Air at standard temperature and pressure is employed as the working gas. The acoustic power source was a l5 W speaker operating at a frequency of 450 Hz. Based on a numerical study, the stack length was set equal to 3 cm with its center located at a distance of 5 cm from the driver-end of a 38.5 cm long resonator tube. The temperature difference between the two ends of the stack was set equal to 25 K.

. The maximum coefficient of performance (COP) of this device was l.5. Further research and development is needed in order to explore the full potential of the device in refrigeration applications.

INTRODUCTION

Recent developments in the field of Thermo acoustic promise to revolutionize the way that many machines currently operate.By manipulating the temperature-changes along the acoustic longitudinal waves, a machine can be created that can replace current refrigeration and air conditioning devices. These machines can be integrated into refrigerators, home generators, hot water heaters, or space heaters and coolers. The Thermo acoustic devices contain no adverse chemicals or environmentally unsafe elements that are characteristics of the current refrigeration systems. Thermo acoustic deals with the conversion of heat energy to sound energy and vice versa. There are two types of Thermo acoustic devices: Thermo acoustic engine (or prime mover) and Thermo acoustic refrigerator. In a Thermo acoustic engine, heat is converted into sound energy and this energy is available for the useful work. In this device, heat flows from a source at higher temperature to a sink at lower temperature.Thermo acoustic Phenomenon Acoustic waves experience displacement oscillations, and temperature oscillations in association with the pressure variations. In order to produce Thermo acoustic effect, these oscillations in a gas should occur close to a solid surface, so that heat can be transferred to or from the surface. A stack of closely spaced parallel plates is placed inside the Thermo acoustic device in order to provide such a solid surface. The gas parcel oscillates due to the oscillations of the piston. Consider four stages of the piston oscillations, which comprise a thermodynamic cycle consisting of four processes. Two of these processes are reversible adiabatic (1 and 3) and the other two are isobaric (2 and 4), as shown in Fig. 1.1. If the temperature gradient at the wall is very small or zero, this process is called heat pumping (or refrigeration). During the first process, the piston moves toward the closed end and compresses the parcel of the gas, and hence the gas parcel wans up. During the second process, heat flows irreversibly from the parcel to the wall, because the temperature of the gas is higher than that of the wall due to compression. During the third step, the piston moves back (i.e. towards the right side), and the gas parcel expands and cools.

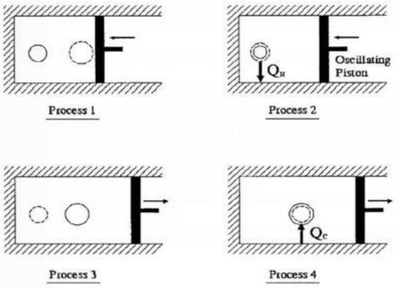


Figure 1.1: Thermoacoustic Cycle.
Solid circle shows the parcel state at the beginning of process and the dashed circle shows the parcel state at the end of process.

Thermodynamic and Acoustic Considerations in a Thermo acoustic Refrigerator

This chapter presents basic thermodynamic and acoustic principles and discusses their contribution to the Thermo acoustic phenomenon. The general working principles of the refrigerator and heat pump, and the thermodynamic behavior of the gas oscillations in the stack channel will also be discussed.

Basic refrigeration theory

The refrigerator is a device that transfers heat from a low-temperature medium to a higher temperature using external work input. The working fluid used in the refrigerator is called the refrigerant. The refrigeration process is based on the first and second law of Thermo acoustic, and its operation is based on one of the thermodynamic refrigeration cycles. The most commonly used refrigeration cycle is the vapor—compression type.

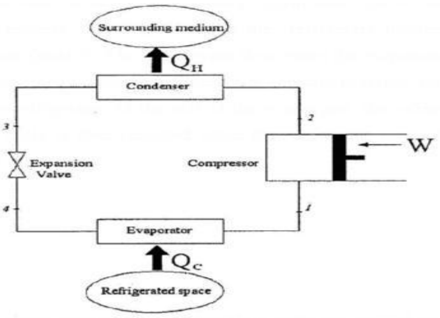


Figure 2.1(a): Basic component of a refrigeration system working on the vapor-compression refrigeration cycle.

LITERATURE REVIEW

Swift G.W. "Thermo acoustic engines and refrigerators." Thermo acoustic deals with the conversion of heat energy to sound energy or vice versa Thermo acoustic cooling devices use the thermo acoustic principle to move heat using sound.

Garrett S. L., Adeff J. A., and Hofler T. J . "Thermo acoustic refrigerator for space applications." Joumal of Thermo acoustics and Heat Transfer, heat is converted into sound energy and this energy is available for the useful work. In this device, heat flows from a source at higher temperature to a sink at lower temperature.

Tijani M.E.H., Zeegers I.C.H., and De Waele A.T.A.M. "Construction and performance of a Thermo acoustic refrigerator." The Thermo acoustic phenomenon occurs by the interaction of the gas particles and the stack plate. When large temperature gradients are created across the stack, sound waves are generated i.e. work is produced in the form of acoustic power (forming a Thermo acoustic engine).

EXPERIMENTAL WORK

Vapor-Compression Refrigeration Cycle

The vapor-compression refrigeration cycle is the most widely used cycle for refrigerators, air-conditioning systems, and heat pumps. It consists of four thermodynamic processes, and involves four main components: compressor, condenser, expansion valve, and evaporator, as shown in Fig. 2.1. The refrigerant enters the compressor as a saturated vapor at a very low temperature and pressure (state l). The compression process takes place inside the compressor. Both the temperature and pressure of the refrigerant increase as a result, and the refrigerant becomes superheated vapor at the exit of the compressor (state 2). At this state, the temperature of the refrigerant is greater than the temperature of the high-temperature medium. The refrigerant then enters the condenser. The heat transfer process takes place in the condenser at a constant pressure, where heat is transferred from the refrigerant to the high-temperature medium. As a result, there is a small decrease in the temperature of the refrigerant as it exits the condenser (state 3). The refrigerant then enters the expansion valve in which the temperature and pressure of the refrigerant drop significantly due to the sudden expansion. At the end of the expansion process, the temperature of the refrigerant becomes lower than that of the low-temperature medium (state 4). The refrigerant then enters the evaporator where heat is transferred from the low-temperature medium to the refrigerant at constant pressure, resulting in a small increase in the temperature of the refrigerant. At the exit of the evaporator, the refrigerant reaches the state l again. The refrigeration cycle is then repeated when the refrigerant enters the compressor [25].

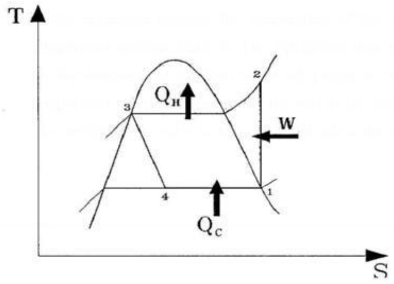


Figure 2.1(b): T-S diagram for the ideal vapor-compression refrigeration cycle.
1-2 Isentropic compression in a compressor.
2-3 Constant pressure heat rejection in a condenser.
3-4 Throttling in an expansion device.
4-1 Constant pressure heat absorption in an evaporator.

Coefficient of Performance (COP) of the Refrigerator

Let TH and TC be the temperatures of high-, and low-temperature mediums, respectively, as shown in Fig. 2.2.

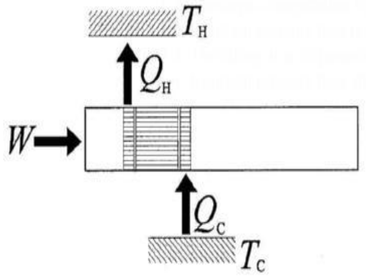


Figure 2.2: A refrigerator, showing the energy flow process.

Also let QC be the amount of heat extracted by the refrigerator from the low-temperature medium and QH be the amount of heat delivered by the refrigerator to the high-temperature medium. If W is the work input to the refrigerator in the form of the compressor work, then according to the first law of thermodynamics.

QH = Qc+ W (2.1)

That is, the amount of energy transferred to the high-temperature medium must be equal to the temperature medium and the work input to the refrigerator [25] Similarly, according to the second law of thermodynamics, Where S is the entropy generation due to the irreversibility [25]. The performance of a refrigerator is measured in terms of the Coefficient of Performance (COP).

It is defined as the ratio of the desired heat transfer to the work input. The main objective of the refrigerator is to maintain the temperature of the low- temperature medium by constantly removing the heat that leaks into the cold space from the surroundings at a higher temperature. Thus, the desired heat transfer for the refrigerator is QC. Hence the COP of the refrigerator is defined as

3.1 Design Considerations

This chapter deals with the design, development and optimization of the Thermo acoustic refrigerator. The linear Thermo acoustic theory presented in chapter 2 will be used for the design analysis. Due to the large number of parameters, a choice of some parameters along with a group of dimensionless independent variables will be used. The optimization of the different parts of the refrigerator will be discussed, and likewise some criteria will be implemented to obtain an optimal system. 3.1

$$\frac{Q_H}{T_H} = \frac{Q_C}{T_C} + (S)_{gen} \qquad (2.2)$$

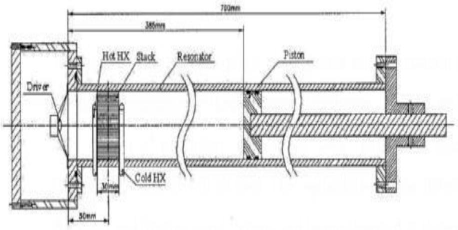


Figure 3.1: Schematic of the thermoacoustic refrigerator.

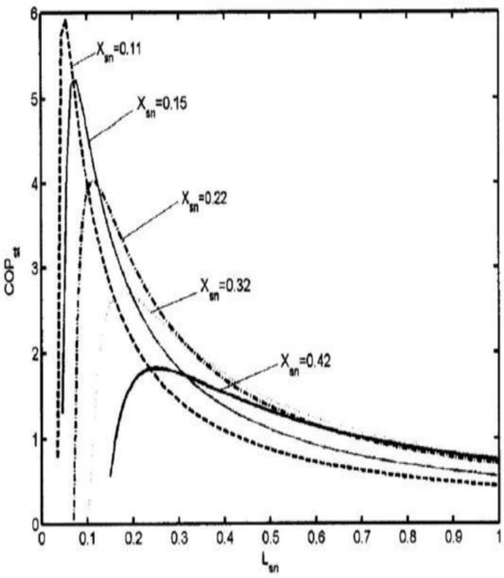
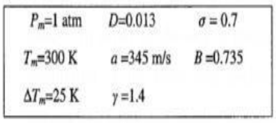


Figure 3.2: The COP_{st} versus the normalized stack length for different values of the normalized stack position. The values are computed at ΔT_m=25 K.

Some of the design parameters used in the present study are tabulated in Table 3.2.



P_m=1 atm	D=0.013	σ = 0.7
T_m=300 K	a =345 m/s	B =0.735
ΔT_m=25 K	γ =1.4	

Table 3.2: The design parameters for the present study.

$$X_{sn} = \frac{2\pi f}{a} X_s \qquad (3.4)$$

$$L_{sn} = \frac{2\pi f}{a} L_s \qquad (3.5)$$

$$\frac{dW_2}{dS}=\frac{1}{4}\rho_m\left|\langle u_1\rangle\right|^2\delta_v\omega+\frac{1}{4}\frac{|p_1|^2}{\rho_m a^2}(\gamma-1)\delta_k\omega \qquad (3.3)$$

Numerical Study In order to develop a Thermo acoustic refrigerator, a numerical study is conducted first. The simulation of the flow was performed to obtain the important design parameters. The important parameters involved in the design of a Thermo acoustic refrigerator are listed in Table 3.1. A Thermo acoustic cooling device such as refrigerator consists of an acoustic driver attached to the acoustic resonator (tube) filled with a working fluid. Inside the resonator tube, a stack of thin parallel plates and two heat exchangers (hot and cold) is installed (see Fig. 3.1).

3.2 Acoustic Driver

The total acoustic power used by the refrigerator is provided by an acoustic driver. A significant portion of this power is used to pump heat in the stack and the rest is dissipated in different parts of the refrigerator. A higher performance of the driver leads to a higher performance of the driver leads to a higher performance of the whole refrigerator system. The Acoustic driver converts electric power input to the acoustic power. As discussed in section 3.2, an acoustic driver with the resonance frequency of 450 Hz was selected for the present design.

Stack Optimization

The most important component of a Thermo acoustic device is the stack inside which, the Thermo acoustic phenomenon occurs. Thus, the characteristics of the stack have a significant impact on the performance of the Thermo acoustic device. The stack material should have good heat capacity but low thermal conductivity. The low thermal conductivity for the stack material is necessary to obtain high temperature gradient across the stack and a heat capacity CA4 larger than the heat capacity of the working fluid. In addition, the stack material should minimize the effects of viscous dissipation of the acoustic power

Where L,"is the length of the stack and X, is the distance from the mid length of stack to the nearest end of the resonator tube. Some other normalized parameters used in the design of the Where AT," is temperature difference across the two ends of stack, Tm is the mean air temperature inside the resonator tube, AT this is the normalized temperature difference, 5,' is thermal penetration depth, and ya is half of the spacing length between the stack layers, and 5,0, is the normalized thermal penetration depth. For the ideal gas and ideal stack, the stack material can be chosen so that as (stack heat capacity ratio) and thermal conductive term in Eqs. (2.44_) and (2.50) can be neglected. Hence Eqs. (2.44) and (2.50) can be written in a dimensionless fonn by using the dimensionless parameters, the gas data of Table 3.1, and es=0 as and the design parameters in Table 3.2, the stack design parameters can be obtained. An important parameter to be considered in the stack design is the temperature difference between the two ends of the stack, AT, Optimization is done based on 25 K temperature difference between the two ends of the stack Afier the temperature difference across the stack is selected, the next task is to determine the normalized length of the stack, LS,,, based on the value of XS", the nominalized stack position. The COP "is plotted against the normalized stack length for different stack positions in Fig. 3.2

$$\Delta T_{mn}=\frac{\Delta T_m}{T_m} \qquad (3.6)$$

$$\delta_{kn}=\frac{\delta_k}{y_0} \qquad (3.7)$$

In order to analyze the impact of AT," on the overall performance of the Thermo acoustic refrigerator, the COP,, is plotted in Fig. 3.6 as a function of the nominalized stack length for different values of AT,,,. The plot shows that the COP "increases as AT," decreases. In order to get the highest cooling power, that is, the maximum heat transfer from the cold end of the stack, for the given four values of AT,,,, the better value of AT,,, is 10 K as QC" at this temperature is greater than that at 5 K (see Fig. 3.5). However the physical length of the stack for AT", = l0 K is 13 mm. This length of the stack is not suitable from the fabrication point of view. Based on the feasibility from the fabrication point of view and the objectives of this study, AT,,, = 25 K was chosen. The stack length at this temperature difference is equal to 30 mm.

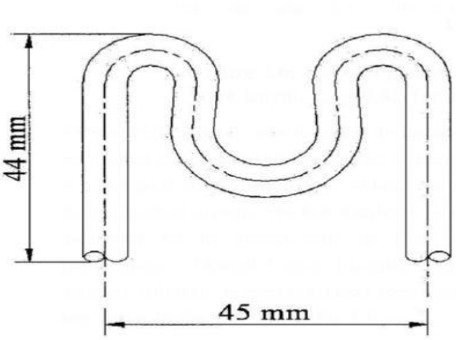


Figure 3.7: Schematic of cold and hot heat exchangers.

In order to exploit the Thermo acoustic effect for heat pumping; heat exchangers are attached at both ends of the stack. Heat exchangers transfer heat from the gas to the external sink or to the gas from an external source of heat. The design of the heat exchangers is a critical task in Thermo acoustical systems. The heat transfer in oscillating flows with zero mean velocity is poorly understood. For the present study, the heat exchangers were designed with the following specifications. 0 Material; Copper. I Length; 12 cm. 0 Tube outer diameter; 3/16 inch. 0 Tube wall thickness; 0.03 inch. In order to get more contact surface between the stack and the copper tube, it has been bent in the form of "M" (see Fig. 3.7)

Working Fluid many parameters such as power, efficiency, and convenience are involved in the selection of the working fluid, and it depends on the application and objective of the device. Thermo acoustic power increases with an increase in the mean pressure inside the resonator. It also increases with an increase in the velocity of sound in the working fluid. The lighter gases such as H2, He, Ne have the higher sound velocity. Lighter gases are necessary for the refrigeration application because heavier gases condense or freeze at low temperatures, or exhibit non ideal behavior. In order to obtain high efficiency and high power, a working gas with low Prandtl number and high sound speed should be chosen [26]. Air at atmospheric pressure is chosen as a working fluid for the present study. 3.7 DeltaE Software DeltaE "Design Environment for Low-Amplitude Thermo acoustic Engine" is a computer program that was developed by the research group at the Los Alarnos National Laboratory

This software solves the one-dimensional wave equation based on the low-amplitude, 'acoustic' approximation. It solves the wave equation for a gas or liquid, in a geometry given by the user. The software can predict how a given Thermo acoustic device will perform, or can allow the user to design a device to achieve the desired performance. DeltaE is a useful to tools for the researchers in physical acoustics, especially Thermo acoustics. It is capable of handling complex geometrical configurations and specialized acoustic elements including resonators, duct networks, and complete Thermo acoustic engines such as prime movers or electroacoustically-driven refrigerators. The software can be downloaded free of cost from the website of the Thermo acoustic research group at the Los Alamos National Laboratory [31]. I the presented study, simulations were performed using the DeltaE software for the design and operating conditions discussed previously. Volume flow rate against the resonator tube is plotted in Fig. 3.8. The plot shows that the maximum flow rate occurs at the middle of the resonator (L=0.l9 m) and is minimum at both ends of the resonator. The volume flow rate at the left end is not zero because the loudspeaker is attached at this end and the velocity is not zero at the end due to the oscillation of the speaker diaphragm. At the solid end (i.e. the right end) the velocity and hence the flow rate is zero, as expected. The location of the stack is also shown in Fig. 3.8. The plot indicates that the volume flow rate at the cold end is greater than that at the hot end. The plot also shows that the volume flow rate does not change by varying the temperature difference across the stack. The temperature inside the resonator is plotted versus the resonator length in Fig. 3.9 for different values of stack temperature gradient.

Results

In this chapter the experimental results are presented in two sections. In the first section, the results before the installation of the heat exchangers are presented and in the second section, the results of the complete system including the heat exchangers are presented.

5.1 Effect of Stack on the Thermo acoustic Phenomenon

In this section, the influence of the stack on the temperature field inside the resonator, and the effect of stack position, resonance frequency and the resonator length on the temperature difference across the stack are discussed.

5.1.1 Temperature Distribution in the Resonator Tube without the Slack

In this set of experiments, the temperature field inside the resonator tube was measured without the stack, in the presence of the acoustic standing wave. This experiment is carried out without incorporating the stack. The temperature at 10 points inside the resonator along the length of the resonator was measured by using thermocouples. The thermocouples were placed inside the resonator 1 cm apart (see Fig. 5.1). The data was acquired for 335 seconds. The time series of the temperature field inside the resonator tube is shown in Fig. 5.2.

The figure shows that the temperature at all points remained almost constant and did not change with time. The maximum variation in the temperature along the resonator tube was 0.5 “C.

5.1.2 Temperature Distribution in the Resonator Tube with Stack The time series of the temperature at the eight locations are plotted in Fig.5.4. The plot shows that initially all locations were at the same temperature equal to 23 °C. When the speaker was tuned on, the standing acoustic wave was created inside the resonator, and the Thermo acoustic process was initiated. Once the Thermo acoustic process started, the parcels of air start transferring heat from the cold end of the stack to the hot-end. As a result, the temperature at the cold-end of the stack started to decrease and the temperature of the hot-end of the stack started to increase. The largest temperature difference was observed between the two ends of the stack. A temperature difference as high as 23 "C was observed across the stack approximately 400 sec after the beginning of the Thermo acoustic process. It was also observed that the temperature difference decreased away from both ends of the stack.

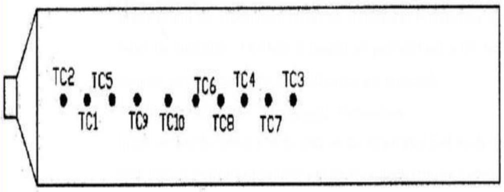


Figure 5.1: Thermocouple positions in the resonator tube without the stack.

The plot in Fig. 5.1 shows that the temperature at the hot-end of the stack increases continuously with time, whereas, the temperature at the cold-end of the stack decreases sharply during the first 110 sec, and remains constant for approximately 90 sec and then increases by 1 °C. Since this is a transient phenomenon, the analytical model, which considers the steady state phenomenon, does not predict this behavior.

The plot in Fig. 5.3 shows the temperature field inside the resonator computed from the experimental data and the numerical simulation using Delta E software. The results show that the temperature gradient just across the stack obtained from the experiments is in good agreement with the computational results. However, the experimentally obtained temperature values in the regions on the left and right sides of the stack do not agree with the computational results.

Conclusions and Suggestions for the Future Work

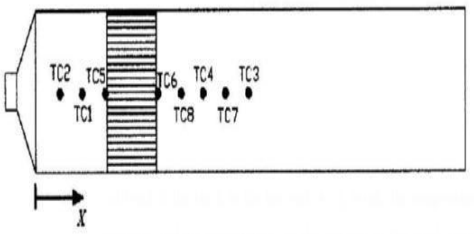


Figure 5.3: The temperature measurement positions in the resonator tube.

Thermo acoustics is a promising area, which if properly explored, could serve as a renewable energy source. In a complete Thermo acoustic system, the heat is used in the prime mover (Thermo acoustic heat engine) to generate acoustic wave. This acoustic wave is then used as an input to the Thermo acoustic refrigerator. Thus, a Thermo acoustic system could use waste heat and drive a refrigerator. However, the efficiency of these devices is currently very low and thus, cannot compete with their conventional counterparts. The main motivation for the present work was to develop a simple Thermo acoustic refrigerator that is completely functional. This thesis reports on the design and development of a simple, low-power Thermo acoustic system for the refrigeration application. The design and development comprised of two parts. In the first part, which is discussed in Chapter 3, different components of the refrigerator were designed based on the given operating conditions from the theoretical analysis. The results have shown that the performance of the refrigerator depends on the working gas, pressure inside the resonator tube, shape of resonator tube, material, position and length of the stack. The performance of the stack was also simulated numerically.

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