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Fabrication and Performance Evaluation of Thermoacoustic Refrigerator

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Abstract: Thermoacoustic deals with the conversion of heat energy to sound energy or vice versa. Therrnoacoustic cooling devices use the thermoacoustic 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 refrigerator was fabricated and performance of the device was then tested. The stack length and the position of the stack in the resonator have a significant impact on the overall performance of the thermoacoustic 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. Preliminary experimental results have shown that a temperature difference of as high as 23 K was established across the stack. In order to exploit the thermoacoustic effect for heat pumping; heat exchangers were attached at both ends of stack. Water at ambient temperature was chosen as the working fluid for the heat exchangers to facilitate heat transfer to or from the stack. A pump was used to circulate water through both heat exchangers. Experimental results have shown that water temperature difference of 3 K for cold heat exchanger and 7.5 K for hot heat exchanger were established. 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.
Keywords: Thermoacoustic, stack, Refrigerator, Resonator tube.

I. INTRODUCTION

Recent developments in the field of thermoacoustics 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 thermoacoustic devices contain no adverse chemicals or environmentally unsafe elements that are characteristics of the current refrigeration systems. Therrnoacoustics deals with the conversion of heat energy to sound energy and vice versa. There are two types of thennoacoustic devices: thermoacoustic engine (or prime mover) and thermoacoustic refrigerator. In a thermoacoustic 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. ln a thermoacoustic refrigerator, the reverse of the above process occurs, i.e., it utilizes work (in the form of acoustic power) to absorb heat from a low temperature medium and reject it to a high temperature medium. The efficiency of the thermoacoustic devices is currently lower than that of their conventional counterparts, which needs to be improved to make them competitive. In addition, other considerations for a competitive thermoacoustic device are low cost, high reliability, safety, compactness and ease of mass production.

A. Thermoacoustic Phenomenon

Acoustic waves experience displacement oscillations, and temperature oscillations in association with the pressure variations. In order to produce thermoacoustic 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 thermoacoustic device in order to provide such a solid surface. The thermoacoustic 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 thermoacoustic engine). In the reverse case, the acoustic work is used in order to create temperature gradients across the stack, which is used to transfer heat from a low temperature medium to a high temperature medium (as the case of a thermoacoustic refrigerator), A thermoacoustic refrigerator consists of a tube filled with a gas.

This tube is closed at one end and an oscillating device (e.g. a piston or loud speaker) is placed at the other end to create an acoustic standing wave inside the tube. To understand the thermoacoustic cycle in a thermoacoustic refrigerator, consider a parcel of gas inside the tube with a piston attached to one end of the tube (as shown in Fig. 1). The gas parcel oscillates due to the oscillations of the piston. Consider four stages of the piston oscillations, which comprises 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. 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 warms 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.

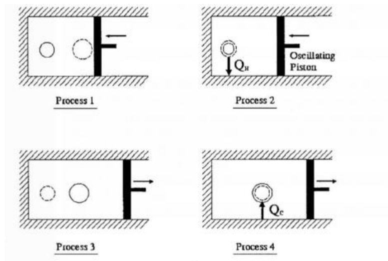

Fig 1: Thermoacoustic cycle. Solid circle shows the parcel state at the beginning of process and the dashed circle shows the parcel state at the end of process

At the end of the third process, the temperature of the gas parcel is less than the wall temperature. During the fourth and last process, heat flows irreversibly from the wall to the gas parcel. At the end of this process, the gas parcel returns to its initial state and the thermoacoustic cycle is completed. Thus, during the complete cycle, 21 net amount of heat is transferred from one end of the tube to the other by the gas parcel under the influence of externally generated oscillations. If this cycle continues, one side of the tube warms up and the other side cools down creating a temperature gradient. The tube mentioned should not be conducting heat in order to maintain the temperature gradient. In conventional systems, pistons are used to compress and move the gas, but in therrnoacoustic devices, compression and displacement occur by the acoustic wave, and the time phasing is necessary to have irreversible heat transfer in steps 2 and 4 because of the time lag between the temperature and the particle motion. It is important to know that all the gas parcel inside the tube do not contribute equally in the thermoacoustic effect. The parcels of gas that are far away from the wall do not have thermal contact with wall. The parcels that are too close to the wall have a good thermal contact but also have significant viscous effects. An optimal distance of the gas parcel for the best performance is the one where the viscous effects are minimal and the thermal contact with the wall is strong enough for the heat exchange. The optimal distance is related to the thermal and viscous penetration depths that will be discussed in detail next.

II. THERMODYNAMIC AND ACOUSTIC CONSIDERATIONS IN A THERMOACOUSTIC REFRIGERATOR

This presents basic thermodynamic and acoustic principles and discusses their contribution to the thermoacoustic 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.

A. Acoustical theory

The understanding of acoustic wave dynamics, i.e. the pressure and velocity fields created by an acoustic wave, is necessary to understand the working of a thermoacoustic device. The acoustical theory deals with the study of the longitudinal acoustic waves. The longitudinal acoustic waves are generated as a result of the compression, and expansion of the gas medium. The compression of a gas corresponds to the crest of a sine wave, and the expansion corresponds to the troughs of a sine wave. An example of how these two relate to each other is shown in Fig. 2. In a longitudinal wave, the particle displacement is parallel to the direction of wave propagation i.e., they simply oscillate back and forth about their respective equilibrium positions. The compression and expansion of a longitudinal wave result in the variation of pressure along its longitudinal axis of oscillation. A longitudinal wave requires a material medium such as air or water to travel. That is, they cannot be generated and/or transmitted in a vacuum. All sound (acoustic) waves are longitudinal waves and therefore, hold all the properties of the longitudinal waves discussed above. Three characteristics of the acoustic wave are necessary for the understanding of the thermoacoustic process. These properties are amplitude, frequency and wavelength. The displacement of a wave from its equilibrium position is called the wave amplitude. It is also a measure of the wave energy. Larger the amplitude, higher will be the wave energy or intensity. Thus, the energy of an acoustic wave can be estimated by measuring its amplitude. The energy or intensity of an acoustic wave is measured in terms of decibel. If the given acoustic wave is comprised of the superposition of different sine waves, then the amplitude and hence the energy of the given wave can be estimated by integrating the energy in all the frequency components of the given wave. The time period of a wave is the time required for the complete passage of a wave at a given point.

The fundamental wave frequency is the inverse of the time period. In other words, it is the number of waves that pass a given point in a unit time. It is typically measured in Hertz (Hz).

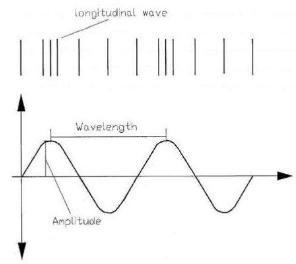

Fig 2 : Comparison of longitudinal acoustic wave with a sine wave

In acoustics, it is also a measure of the sound pitch. Higher the frequency, higher will be the pitch. The wavelength is defined as the horizontal distance from the beginning of the wave to the end of the wave. It can also be measured as the distance from one wave crest to the next wave crest, or one wave trough to the next wave trough.

In acoustics, we can define wavelength as the distance between the two successive compressions or expansions.

As mentioned earlier, the compression and expansion of an acoustic wave result in pressure variations along the waveform. This pressure variation is the key process that causes the thermoacoustic phenomenon. These pressure variations can also be used to estimate the sound intensity. Eq. 1 outlines how the sound intensity, L, in decibels can be estimated from the pressure measurements at two points. The decibel (dB), or one- tenth of a bel, is twenty times the logarithm of the ratio of the sound pressure to a reference pressure. This unit measures sound pressure level, and is useful because the ear hears sounds exponentially. Eq. 2. outlines how L, the sound pressure level in units of decibels, is calculated using the measured sound pressure P to the reference pressure Pm. Pm; is the pressure corresponding to the threshold of hearing and is 0.00002 N/m2.

As a sound wave registers more decibels, it sounds louder.

$$L = 20\log_{10} P/P_{ref}; \text{ --- Eq 1.}$$

The equation indicates that larger the pressure variations, higher will be the sound intensity, or vise versa.

$$P = pRT \quad \text{----Eq 2.}$$

Where P is the pressure, p is the density, T is the absolute temperature, and R is the gas constant. The above equation indicates that if the density variations are very small, the change in pressure causes the change in temperature. That is, an increase in pressure causes an increase in temperature and vice versa.

B. Thermodynamic Considerations

In this section, we will discuss the thermoacoustic phenomenon based on acoustics and thermodynamics. To understand the phenomenon, consider a thermoacoustic cooling device such as refrigerator. This device consists of an acoustic driver attached to an acoustic resonator (tube) filled with the working fluid. Inside the resonator tube, a stack of thin parallel plates and two heat exchangers (hot and cold) are installed for the heat transfer. The schematic of a typical thermoacoustic device is shown in Fig. 3 (a).

The acoustic driver, connected to one end of the resonator tube, excites the working fluid (typically a gas with low Prandtl number), and creates a standing acoustic wave inside the tube. Hence the gas oscillates inside the resonator with expansions and compressions.

For simplicity, the effect of viscosity and the longitudinal thermal conductivity in the gas are neglected.

The length of the resonator tube is typically set equal to one-half of the wavelength of the standing wave, i.e l /X2.

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The standing wave creates velocity nodes at the two ends of the tube and a pressure node at the middle of the tube (see Fig. 3 b). If a stack of parallel plates is placed inside the tube, the gas will be at a higher pressure at the end of the stack, which is closer to the end of the tube (i.e. left side of the stack in Fig. 3 a), than the other end of the stack. This high pressure results in an increase in the temperature of the gas and the excess heat is transferred to the stack, causing an increase in the temperature of the stack at that end and an average longitudinal temperature gradient, along the stack is established (see Fig.3 c).

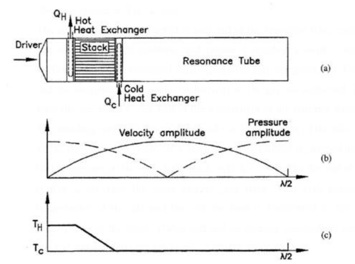

Fig 3: (a) Schematic of a thermo acoustic refrigerator. (b) The velocity and pressure variations across the resonance tube.(c) Temperature variation across the resonance tube

1) *Length Scales in Thermoacoustic Systems:* In a thermoacoustic refrigerator, two characteristic length scales of the stack are important from the design considerations. One is called the thermal penetration depth and the other is called the viscous penetration depth. The thermal penetration depth, corresponds to the thickness of the layer around the stack plate through which the heat can diffuse during a complete oscillating cycle of a gas parcel. It is defined as,

$$\delta_k = \sqrt{\frac{2K}{\rho C_p \omega}}$$

Where, K is thermal conductivity of the gas, CP, is specific heat per unit mass at constant pressure, p is density of gas at the mean temperature (Tm) and ω is the angular velocity. That is, w=2πf, where f is the frequency of the acoustic wave.

III. FABRICATION AND EXPERIMENTAL SETUP

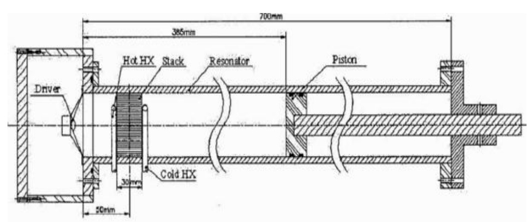

Fig 4: Schematic of the thermo acoustic refrigerator

In this, the fabrication of the thermoacoustic refrigerator is described, which is followed by the description of the experimental setup, instrumentation and methods for the measurements in the fabricated refrigerator.

A. Fabrication

The details of each component are described (see Fig. 4.).

1) *Acoustic driver:* A thermoacoustic cooling device requires an acoustic driver attached to one end of the resonator, in order to create an acoustic standing wave in the gas at the fundamental resonant frequency of the resonator. The acoustic driver converts electric power to the acoustic power. In this study, a loudspeaker with the maximum power of l5 watts, and impedance of 8Q at the operating frequency (450 Hz) was used as the acoustic driver (G 50 FFL, VISATON). The loudspeaker was driven by a function generator and a power amplifier to provide the required power to excite the working fluid inside the resonator. Efficiency of this type of loudspeaker is relatively low, and their impedances are poorly matched to gas when the pressure inside the resonator is high. Consequently, the range of pressure amplitudes inside the resonator is limited.
2) *Acoustic Resonator:* The acoustic resonator was built from a straight acrylic tube of length 70 cm. The internal diameter of the tube was 6.3 cm and the wall thickness was 6 mm. One end of the tube has a plate attached to install the speaker frame. At the

other end, a movable piston was placed inside the resonator. The reason for having a movable piston was to adjust the length of resonator so as to change the fundamental resonant frequency of the resonator (see Fig. 4.). In the present design the resonance frequency of the resonator is 450 Hz. Thus, the length of resonator tube was set equal to 38.5 cm that corresponds to the half-wavelength of the acoustic standing wave generated at this frequency. The resonator was sealed at both ends with the rubber O-rings to minimize the sound energy leakage.

3) *Stack:* In this project, a spiral stack with parallel-plate geometry was used. The stack was made from the mylar sheet of thickness 0.13 mm. The mylar sheet was cut into pieces, each 3 cm wide. The spacing between the layers was realized by fishing line spacers (0.36 mm thick) glued onto the surface of the sheet. The distance between the two layers, i.e. 0.36 mm. The mylar sheet was wound around a 4 mm PVC-rod to obtain a spiral stack as shown in Fig. 5.

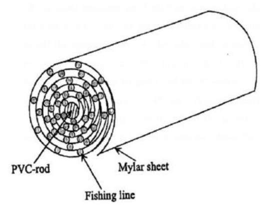

Fig 5: An illustration of spiral stack

4) *Heat exchangers:* The two heat exchangers were built from the 3/16" diameter copper tube. To improve the performance of the heat exchangers, the tubes are bent in the form of “M” (see Fig. 6). The total length of each exchanger is equal to 12 cm. The design of the heat exchangers is critical in thermoacoustics. Since they are placed in front of the stack, they block the motion of the gas particles and hence disturb the thennoacoustic process. Therefore, the heat exchangers have to be designed in a way to minimize the disturbance to the particle motion and to have the effective heat exchange between the stack and the heat exchanger fluids.

5) *Assembly:* A schematic illustration of the thermoacoustic refrigerator pans is shown in Fig. 7. It consists of an acoustic driver housing, an acoustic driver, two heat exchangers, stack, a resonator filled with air at atmospheric pressure, position adjustable piston and piston support.

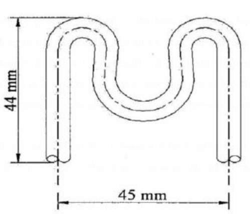

Fig 6: Schematic of cold and hot heat exchangers

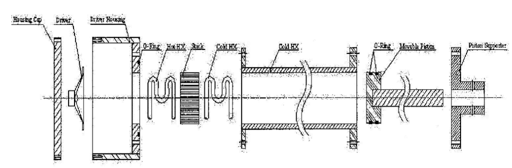

Fig 7: Schematic illustration acoustic refrigerator

Four holes were made in the resonator tube to place heat exchangers inside the resonator tube.

The first step is to place the cold heat exchanger inside the resonator. The second step is to mount the stack and then the hot heat exchanger. Two thermocouples were attached to both sides of the stack. The inlets and outlets of both heat exchangers were extended from the resonator tube and connected with rubber pipes for the flow of water through the heat exchangers.

After passing the inlet and outlet of both heat exchangers from the resonator tube wall, the holes were sealed by glue. Third step is to put the position adjustable piston into the resonator tube. Two grooves were cut on the surface of the piston where the two rubber O-rings were placed to seal the piston. The microphone was mounted in the piston to move along with the piston in the resonator. After the movable piston is mounted into the resonator tube, the support was attached to the resonator tube via six M5 bolts. Its role is to support and guide the piston. The next step is to attach the acoustic driver in its housing with the resonator tube via six M5 bolts. A groove was cut on the surface of the acoustic driver housing where a rubber O-ring was placed to seal the resonator tube. Four thermocouples were attached to the inlet and outlet of heat exchangers to measure the inlet and outlet temperatures of the circulating water through both heat exchangers.

B. Instrumentation

This section details the instrumentation used to collect the experimental data in the refrigerator

1) *Sensors:* One microphone and ten thermocouples were used in the experiments to measure the sound intensity and temperature, respectively.

   a) *Microphone:* A condenser microphone cartridge Model 377Al0 PCB Piezotronics was used to measure the sound intensity level and dynamic pressure amplitude inside the resonator when the loudspeaker was excited. The microphone consists of a microphone cartridge and a microphone preamplifier. A preamplifier Model 426B03 was used in order to measure the sound intensity. The cartridge screws directly onto the preamplifier housing. Frequency responses are almost flat between 5Hz and 100 kHz. The microphone was placed in the adjustable piston as shown in Fig. 4.5. In this case microphone and piston are always at the same position i.e. at the pressure antinode, and it can always measure the maximum pressure.
   b) *Thermocouple:* T-type thermocouples were used for the temperature measurements in this study. They were used to measure the temperature at different locations inside the resonator and the temperature of heat exchanger fluids. The specifications of the thermocouple are given below:

I Thermocouple Grade:-200 to 3500C

Limits of Error: 1 0C or 0.75% above 00C

The output of the thermocouple is very low (0.263 millivolts). A signal conditioner (SCXI-1102) was used to amplify and increase the signal-to-noise ratio of the original signal. The accuracy of the temperature measurement is 1 0C.

2) *Electronic Devices:* A Function generator model Agilent 33120A was used that could generate sine waves with different frequencies or sweep the frequency from 10 Hz to 2500 Hz, to drive the loudspeaker. An amplifier (MPA-25, Realistic) with the maximum power output of 20 watts was used to amplify the power input to the loudspeaker to increase power input. In order to acquire, process and analyze the microphone signal data, a signal analysis unit type 2035 Bruel & Kjaer and an amplifier (PCB 482AO6, Piezotronics) were used.

   a) *Electronic Metering Pump:* The EZ series electronic metering pump model EZBl0Nl-VE was used to pump water through the cold and hot heat exchangers. It consists of a pump unit, a drive unit, and a control unit. The drive unit is electromagnetic solenoid type. The specification of the pump are listed below:

Maximum Output per Stroke .... 0.11 mL

Minimum Output per Stroke .... 0.05 mL

Maximum Pressure .... l MP

3) *Data Acquisition:* A 16 channel data acquisition card (PCI-603615) was used for the data acquisition. The card was installed in the PC. LabView software was used for the data acquisition. The temperature data from all thermocouples and the sound signal from the microphone were acquired simultaneously.

C. *Measurement procedure*

The Schematic of the complete electronic circuit and flow chart are shown in Fig. 4.6 and Fig. 4.7, respectively. The measured procedure is described below. The function generator was used to generate the sine wave at 450 Hz. The wave was then amplified by the power amplifier to increase the power input to the loudspeaker. The following measurements are made:

Temperature (Thermocouple).

Sound intensity (Microphone).

Voltage and current (Loudspeaker).

The acquired data were stored on the hard drive of the PC. For each experiment two to four experimental runs were conducted to check for the consistency in the measured data. To check the accuracy of the data acquisition card, the current and voltage of the loudspeaker acquired by the card was computed with the corresponding data from the oscilloscope. The difference between the two was less than 1%. A photograph of the experimental setup instrumentation is shown in Fig. 8. These types of experiments were conducted:

Measurements inside the resonator without the stack and heat exchangers.

Measurements inside the resonator with the stack but without the heat exchangers.

Measurements inside the resonator with the stack and heat exchangers (i.e. the complete refrigerator)

During the third type of the experiments, the electropump was used to circulate the water through both heat exchangers.. The experimental setup and experiments were described and the methods for acquiring the data and measurement were explained. The experimental results will be present in the next chapter.

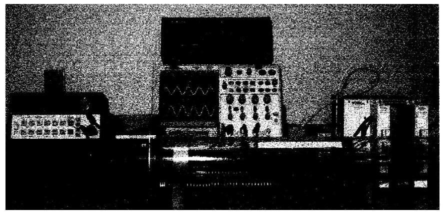

Fig 8: Experimental setup for stack effect on thermoacoustic phenomenon

IV. RESULTS & DISCUSSION

In this 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.

A. *Effect of Stack on the Thermoacoustic 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.

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. 9). the data was acquired for 335 seconds. 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 0.50C.

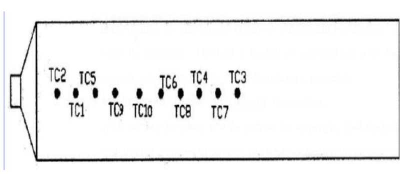

Fig 9: Thermocouple positions in the resonator without stack

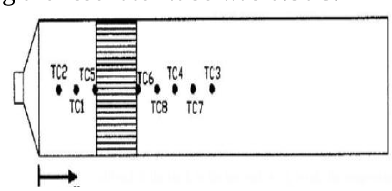

Fig 10: The temperature measurement positions in the resonator tube

2) *Temperature Distribution in the Resonator Tube with Stack:* In this set of experiments, the effect of the stack on the temperature field inside the resonator was investigated. The stack was mounted inside the resonator at XX=5 cm and the acoustic standing wave was generated inside the resonator.

The temperature was measured at eight points along the centerline of the resonator tube. Two thermocouples were placed on the left side of the stack, and four thermocouples were placed on right side of the stack.

One thermocouple was attached to each side of the stack (see Fig. 5.3). The distance between the thermocouples was set equal to 1 cm except, the ones that were at both sides of the stack. The data was acquired for 420 seconds.

The plot in Fig. 11 shows the temperature field inside the resonator computed from the experimental data. 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. The experimental data shows that at the hot side of the resonator, as X decreases from 30 mm to 10 mm, the temperature decreases from 410C to 320C. Similarly, at the cold side of resonator, as X increases from 60 mm to 100 mm, temperature increases from 180C to 21.50C. The hot-end of the stack has the highest temperature and the cold-end of the stack has the lowest temperature inside the resonator. The main reason for this difference between theoretical and experimental results at the cold and hot side of resonator may be due to lack of good insulation. In our experiment the resonator tube is not insulated and heat is transferred between inside and outside the resonator tube.

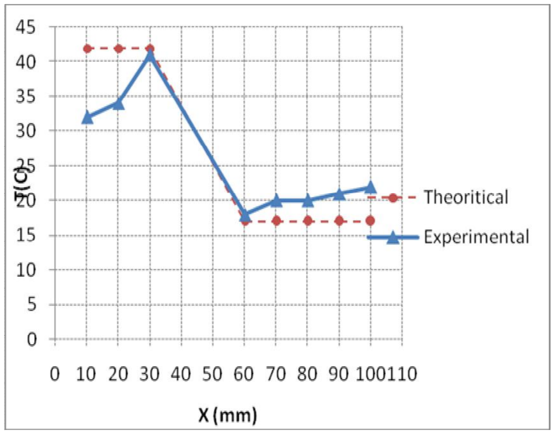

Fig 11: Comparision of the experimental and theoritical temperature distribution inside the resonator tube.

3) Stack Position in the Resonator Tube for Maximum Temperature Difference

The position of the stack inside the resonator is crucial for the optimum performance of the themioacoustic refrigerator, as mentioned in above section. To confirm the validity of the stack parameters obtained from the theoretical design, the position of stack (Xx) inside the resonator tube was changed from 40 mm to 190 mm (half of the resonator tube length) inside the resonator tube in 1cm increments. The power input to the speaker and operating frequency remained constant during the experiments. The temperature difference across both sides of stack was measured in each experiment for 350 sec, and the maximum temperature difference at t =350 second plotted in Fig. 12 against the stack position. The plot shows that as the stack position changed from 190 mm to 50 mm (i.e. close to a pressure antinode), the temperature difference increased from 10C to 23 °C. Further change in the stack position resulted in a decrease in the temperature difference. It shows that the optimum value for stack position to get maximum temperature difference is 50 mm which is in complete agreement with the theoretical study.

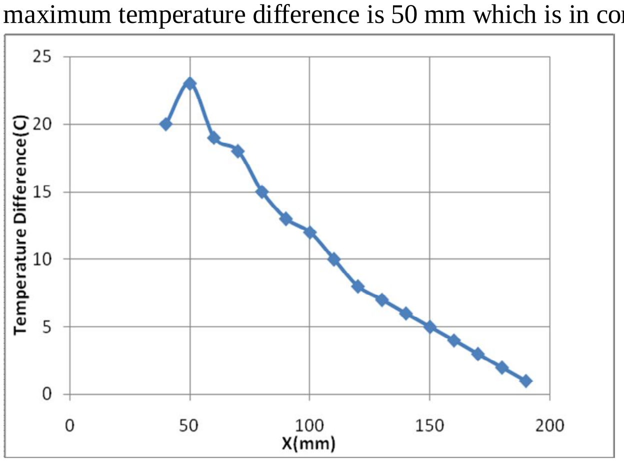

Fig 12: Stack position versus the temperature difference across the stack.

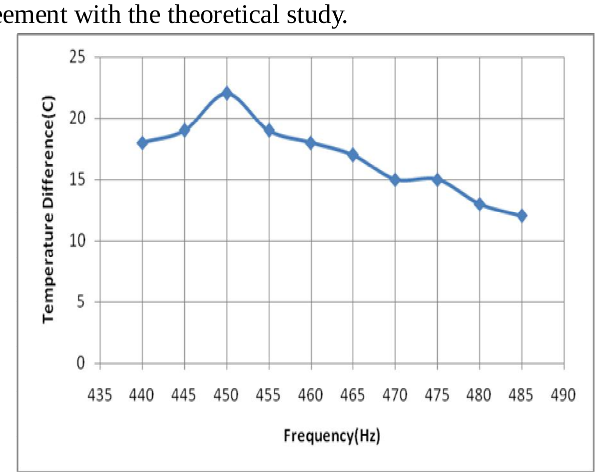

Fig 13: Operating frequency versus temperature.

The temperature difference across the stack against operating frequency is plotted in Fig. 13. The plot shows that as operating frequency decreases from 485 Hz to 450 Hz temperature difference increases from l2 0C to 22 0C. Further decrease in frequency results in a decrease in the temperature difference. In conclusion, the optimum value of the operating frequency for this type of speaker with 385 mm length of resonator tube is 450 Hz which corresponds to half the length of the standing wave. .

4) The Effect of the Power Input on the Temperature Difference at Stack

The temperature difference at both sides of the stack at time t=190 second is plotted in Fig. 14 against power input to the speaker. The plot shows that as power input increased from 4.3 W to 12.7 W, the temperature difference increased from 12.50C to 230C. The plot also shows that for the power input greater than 7 W, the stack-end temperature difference increases almost linearly with the power input.

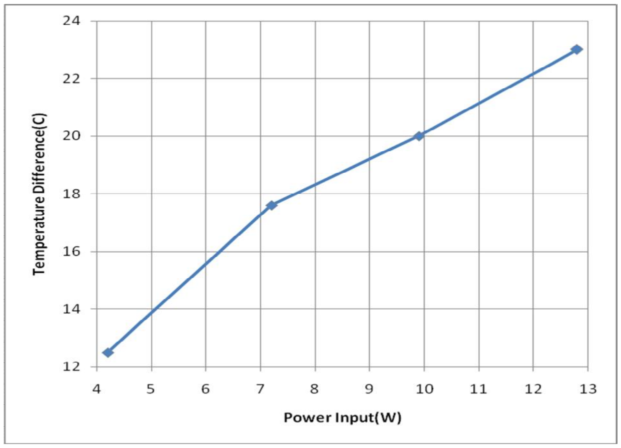

Fig 14: Temperature difference across the stack ends versus the input to the speaker.

B. Performance Characteristics

In the next phase of this study, heat exchangers were attached to each end of the stack and detailed measurements of temperature, pressure and sound inside the resonator were canied out. Once the heat exchangers were incorporated at both ends of the stack, the heat was extracted from the circulating fluid at the cold-end heat exchanger and, heat was added to the circulating fluid at the hot-end heat exchanger, without any significant effect on the air surrounding the stack. In this series of experiments, eight thermocouples were used to measure the temperature at both sides of the stack, water temperatures at inlet and outlet of the cold and hot heat exchangers and also at the surface of both heat exchangers (sec Fig. 15). During these experiments the electro pump was used to circulate water through the hot and cold heat exchangers. The stack was placed at the optimum position, and the acoustic driver was driven at 450 Hz with a power input of 15.5 W.

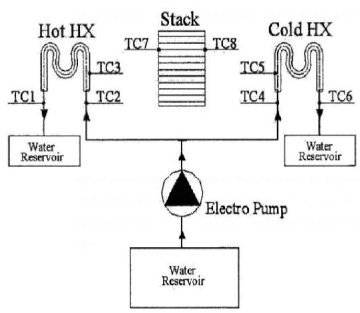

Fig 15: Schematic diagram showing the thermocouple position

1) *The Effect of Power Input on the Heat Transfer Rate in the Cold and Hot Heat* **Exchangers** In this set of experiments, the effect of the power input on the heat transfer rate in both heat exchangers was investigated.

The operating frequency, the stack position and the flow rates of water in both exchangers were maintained constant. The power input to the acoustic driver was changed. At each value of the power input, the temperature of Water at the inlet and exit of both heat exchangers and water flow rate of both heat exchangers were recorded. The difference in the water temperatures between the inlet and outlet for cold and hot heat exchangers are plotted in Fig. 16 against the power input. The power input during these experiments varied from 4 W to 14.6 W.

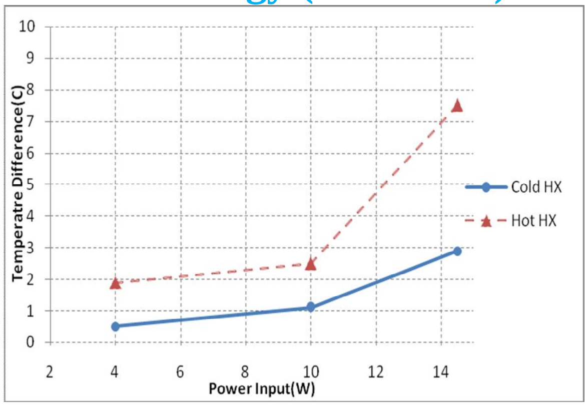

Fig 16: The difference of water temperature between the inlet and outlet versus the power input.

The plot shows that as the power input increases, the temperature difference between the inlet and outlet also increases for both heat exchangers. In a heat exchanger, if the mass flow rate is constant, the temperature difference of the fluid between the inlet and outlet is proportional to the heat transfer rate. Thus, based on the given plot, it can be concluded that as the power input increases, the heat transfer rate in both heat exchangers also increases. The plot also shows that for a given power input, the heat transfer rate in the hot heat exchanger is higher than that of the cold heat exchanger. It also indicates that when the power increased from 4 W to 10 W, the heat transfer rate in both heat exchangers was low. But when the power further increased, the heat transfer rate increased relatively rapidly. The increase in the heat transfer rate in hot heat exchanger was relatively sharp.

2) The Impact of Water Flow Rate on the Water Temperature Difference across the Heat Exchangers

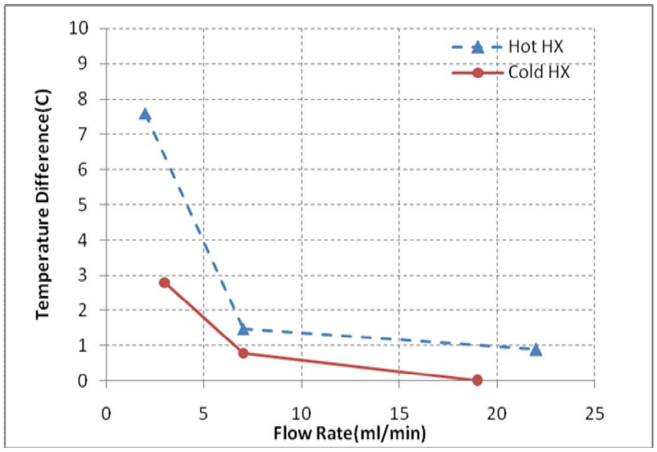

Fig 17:water temperature difference at both heat exchangers versus the electro pump flow rate.

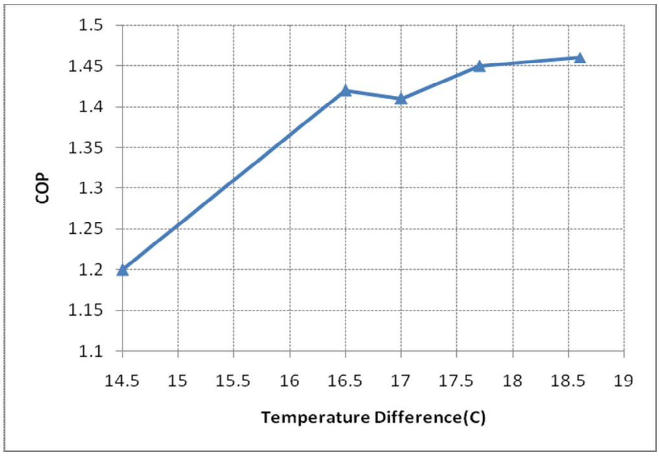

Fig 18: The COP of the thermoacoustic refrigerator vs stack temperature difference. D= 0.0125, pm = 1atm.

In this set of experiments, the operating frequency, the power input and the stack position remained constant. The flow rate of water in the hot heat exchangers was varied from 1.5 rnl/min to 21 ml/min, and the flow rate of water in the cold heat exchanger was varied from 2.6 ml/min to 19.5 ml/min. The temperature difference of water between the inlet and outlet of both exchangers is plotted versus the flow rate in Fig. 17. The plot shows that as the flow rate increases, the difference of water temperature between the inlet and outlet decreases. At a given power input, frequency and the stack position, the heat transfer rate across the stack remains the same. In other words, the heat removal capacity at the cold-end and heat delivery capacity at the hot-end remains the same.

The energy balance equation can be written as, $Q = mCP\ dT$

where Q is the heat transfer rate, m is the mass flow rate, CP, is the specific heat and dT is the fluid temperature difference between the inlet and outlet. Based on the above equation, for a constant heat transfer rate, an increase in the mass flow rate will result in a decrease in the temperature difference.

The coefficient of performance against the stack temperature difference is plotted in Fig. 18. The figure shows that COP increases as temperature difference increases. It also shows that the coefficient of performance was maximum when the temperature difference was 18.60C. This value is different from the design value which is 250C. The energy dissipation increases by adding the heat exchangers, which also change the blockage ratio. Thus, the difference in the experimental and theoretical values could be due to the installation of heat exchangers.

The two major conclusions based on the results presented in this section are:

1) There was no temperature gradient along the resonator centerline without stack. However, a temperature difference as high as 230C is established across the stack by adding stack inside the resonator tube.

2) Once the heat exchangers were incorporated, temperature difference as high as 70 C at the hot heat exchanger and a temperature difference as low as 30 C at the cold heat exchanger are established.

In this chapter the experimental results were presented for three set of experiments:

Measurement inside the resonator without the stack and heat exchangers.

Measurement inside the resonator with the stack but without the heat exchangers.

Measurement inside the resonator with the stack and the heat exchangers (i.e. the complete refrigerator).

V. CONCLUSIONS

Based on the results of the present investigations the following conclusions are drawn:

Without the stack the temperature along the resonator tube is almost constant and the variation is within 1 0.50 C.

Temperature distribution along the resonator is significantly effected by the presence of the stack. After 330 sec of operation a temperature gradient of 23 °C was established across the stack.

The position of the stack is important in order to get the maximum temperature gradient across the stack. For the resonator of 38.5 cm the position of the stack for maximum temperature gradient across the stack is 5 cm.

The operating frequency is important in order to get the maximum temperature gradient across the stack. For the resonator of 38.5 cm the operating frequency for maximum temperature gradient is 450 Hz.

A stack with homogenous structure is important to get the maximum temperature gradient across the stack.

The power input is important to get the maximum temperature gradient across the stack; therefore an efficient acoustic driver is very important to get better COP.

The cooling power of 0.45 W is provided by the device.The Coefficient of performance of refrigerator is approximately 1.5.

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