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Experimental Investigation of a Thermoacoustic Refrigeration System

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Abstract - Thermoacoustic refrigeration is gaining prominence as a green alternative to the traditional cooling devices because of its environmental friendliness. The device generates acoustic waves which compress and expand working gases in a resonator to establish a temperature difference along a stack. Experiments were carried out on the device with a set-up that included an acoustic driver, resonator tube, stack, heat exchanger and temperature measuring instruments. From observations, it was noted that there was a gradual decline in temperatures in the cold region and a corresponding rise in temperatures at the hot region of the stack. This indicates the presence of thermoacoustic heat transfer in the device. Performance depends on various parameters, including frequency of the sound wave, the stack structure and characteristics of the working gas. It is less efficient than the normal refrigerators, but its advantage is that it is simple and maintenance-free.

***Key Words*:** Thermoacoustic refrigeration, Acoustic waves, Heat transfer, Sustainable cooling, Standing wave, Eco-friendly system

1. INTRODUCTION

The process of refrigeration plays an integral role in many modern applications of engineering, starting from preserving foods to cooling processes in industries. Refrigeration techniques that use vapour compression cycles have been traditionally utilizing refrigerants like chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs). Although these chemicals are very effective in their functions, they also create significant environmental problems, which calls for more environmentally friendly solutions.

The thermoacoustic refrigerator is one of the most popular alternatives that have been explored in recent times. This technology uses acoustic waves and a compressible medium in generating cooling without the use of any chemical refrigerants. In this regard, the generation of acoustic waves in the compressible medium leads to changes in pressure. As a result of the oscillations created in the compressible medium inside a resonator, cooling takes place.

The structure of a conventional thermoacoustic refrigerator includes components such as the acoustic driver, resonant tube, stack, and heat exchanger. The acoustic driver creates high-amplitude sound waves which create standing waves in the resonator. The stack enables heat exchange between the oscillating gas and solid materials, thereby creating a temperature difference across two ends – hot and cold ends. Heat can be extracted using the heat exchanger on the hot end while heat is absorbed on the cold end.

Although it offers some advantages like ease of use, stability, and eco-friendliness, thermoacoustic cooling systems have been observed to be less efficient than other systems. In this regard, experimentation is required to determine how different design and operational parameters affect the system's performance. This paper examines the operation principles and performance characteristics of a thermoacoustic cooling system using experimental techniques.

2. LITERATURE REVIEW

The concept of thermoacoustic refrigeration has been widely researched as an eco-friendly substitute for traditional refrigeration systems. The core idea revolves around the interconnection of acoustic phenomena with heat transfer mechanisms within a compressible fluid medium, whereby the pressure change of gases results in the creation of temperature differences. Earlier researches have confirmed that it is indeed possible to produce cooling with the use of acoustic energy.

Various studies have been carried out concerning system optimization via analysis, computation, and experimentally. The study of heat transfer processes and sound has helped gain knowledge about the nature of thermoacoustic effects. Models have been extensively employed to determine the temperature profile and pressures, thus helping optimize the performance of system components such as the resonator and stack.

The importance of various design parameters including the frequency of operation, characteristics of the working gas, stack geometry, and size of resonators has already been pointed out by many researchers. It has also been found that proper choice of these design parameters plays a vital role in the efficiency of the heat transfer process. It is noteworthy that proper design of the stack enhances the heat transfer effect from gas to solid.

Although much progress has been made, some issues still exist. The thermoacoustic refrigerator is known for having less efficiency than traditional refrigerators because of factors like acoustic damping and heat transfer losses. Moreover, most research has been conducted using benchtop prototypes, and there has been no application or comparative study on various designs.

Hence, additional experiments must be conducted to determine optimal design parameters of the thermoacoustic refrigerating unit. This research is intended to solve this problem through performing experiments on thermoacoustic refrigerating system behavior.

3. METHODOLOGY

This work is concerned with the design and experimental investigation of a thermo-acoustic cooling system based on standing waves. The experimental setup includes the design and testing of the device on a small scale in the laboratory. The experimental setup comprises an acoustic driver,

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resonator tube, stack, heat exchanger, and temperature sensors.

All components of the device were chosen and placed in such a way that acoustic waves could be formed successfully and heat could be transferred from the gas to the solid efficiently. The stack was located at a convenient spot inside the resonator for efficient thermal interaction between the vibrating gas and solid structures. Thermocouples were installed on both ends of the stack to measure temperature difference in the process of operation.

The system operation was carried out through applying electricity to the acoustic driver to generate high-powered sound waves inside the resonator. Sound waves made the gas vibrate creating temperature difference. This temperature difference was recorded in due time periods till the steady state was reached. Obtained results helped evaluate cooling ability of the device.

The overall operation of the thermoacoustic refrigeration system can be understood through a block representation of its main components and energy flow.

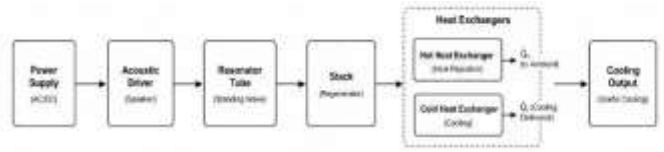

Fig -1: Block Diagram of Thermoacoustic Refrigeration System

As shown in Fig. 1, the acoustic driver generates sound waves which propagate through the resonator and produce cooling via heat exchangers.

3.1 WORKING PRINCIPLE

The principle of thermoacoustic refrigeration relies on the effects of acoustics and thermodynamics on a compressible fluid. With the propagation of acoustic waves in the gas medium, there are alternating pressure and expansion cycles of the gas molecules. There is an increase in the temperature of the gas during compression and a decrease in temperature during expansion.

In the process, there is a transfer of energy in terms of heat from one point to another. The oscillating gas molecules come into contact with the stack walls, with the heat being absorbed by the wall during expansion and released by the wall during compression. The effect of this is the development of a temperature gradient along the stack, whereby one side gets hotter than the other.

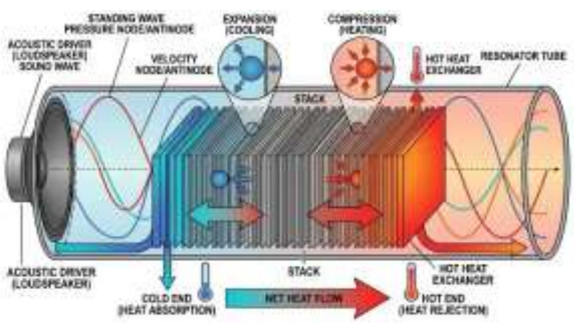

Fig -2: Working Principle of Thermoacoustic Refrigeration

As illustrated in Fig. 2, compression leads to heating while expansion causes cooling, creating a temperature gradient across the system.

3.2 GOVERNING EQUATIONS

The behaviour of the thermoacoustic cooling system is defined by basic laws of acoustics and thermodynamics. The formula of the speed of sound and its connection to frequency and wavelength is expressed as follows:

$$c = f\lambda$$

The formula for finding the resonator's length of the standing wave system is defined as:

$$L = \frac{\lambda}{4}$$

The relation between the temperature and pressure at the point of compression and decompression is described by the following formula:

$$T \propto P^{(\gamma-1)/\gamma}$$

These equations are essential for designing the resonator and understanding the thermoacoustic effect within the system.

3.3 SYSTEM PARAMETERS

The operation of the thermoacoustic refrigeration system depends on several parameters that are important for its operation. Frequency is one of the main parameters influencing the resonance process. The density of the working fluid, its thermal conductivity, and specific heat capacity will have an impact on the acoustic wave propagation and heat exchange processes.

The design of the stack also matters, and the size of the plates and their composition will affect heat exchange between the gas and solid bodies. The dimensions of the resonator will also influence the creation of standing waves.

Table -1: Properties of Working Gases

Gas	Density (kg/m³)	Thermal Conductivity	Speed of Sound
Air	1.2	0.026	343
Helium	0.178	0.15	1007
Nitrogen	1.25	0.025	349

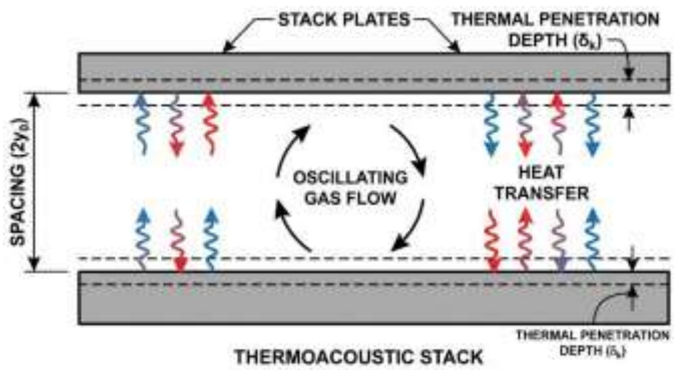

Fig -3: Working Principle of Thermoacoustic Refrigeration

As shown in Fig. 3, proper spacing between stack plates enhances thermal interaction and improves system performance.

4. EXPERIMENTAL SETUP

The experimental set-up of the thermoacoustic refrigeration device was designed in order to illustrate the phenomenon of cooling created by acoustic waves. This includes such components as the acoustic driver, the resonator tube, stack, heat exchangers, buffer volume, and devices for monitoring temperature in a compact arrangement.

The acoustic driver, in the form of a speaker, is attached to a source of electrical energy and creates high-intensity sound waves. Such waves travel along the resonator tube and create conditions for the creation of standing waves. The resonator should be configured to provide correct acoustic conditions that will ensure thermoacoustic performance.

Stack is inserted in the resonator, but at a proper position to allow the interaction of gas vibration and solid surfaces. This interaction results in heat exchange and formation of temperature gradient. The heat exchangers are installed at both the ends of the stack, with one heat exchanger receiving heat from the surroundings and the other releasing heat into the surroundings.

There is provision for a buffer volume in the experiment to minimize fluctuations of the pressure within the system. platinum resistance temperature detector (PT100) temperature sensors are installed at the ends of the hot and cold stacks to monitor temperature variation during the operation of the equipment.

The whole assembly is fixed onto a solid metal framework to guarantee stability and correct positioning of all the parts. This helps produce acoustic waves and measure the change in temperature.

Fig -4: Experimental Setup of Thermoacoustic Refrigeration System

Fig. 4 shows the arrangement of components including the acoustic driver, resonator tube, stack, and measurement instruments.

5. RESULTS AND DISCUSSION

Thermoacoustic refrigeration device performance was assessed using measurements taken for temperature fluctuations at the hot and cold ends of the stack with time. The results from the experimental analysis show that there is clear formation of a temperature gradient during the operation of the device.

At first, the temperatures on both sides of the stack were uniform, with both sides having almost 30 degrees Celsius in temperature. However, with the continued use of the device, there was an increase in temperature on the hot side of the stack, while at the same time, there was a decrease in temperature on the other side of the stack. After the operation of the stack for ten minutes, the hot end temperature had risen to approximately 42 degrees Celsius, while on the other end, it had dropped to 22 degrees Celsius. This shows heat transfer by thermoacoustic within the system.

This phenomenon indicates that the acoustic waves successfully bring about the process of periodic compression and rarefaction of the working fluid leading to heat transfer from one region to another. The rate of heat loss was higher initially and slowly decreased with time as the system attained equilibrium.

The relationship between temperature and time from a graphical point of view is yet another proof of the experimental results. There is a stable rise in temperature in the hot side of the apparatus, but there is a constant fall in temperature until a stable situation is achieved in the cold side. These results agree with the basic concept of thermoacoustic refrigeration, which involves the conversion of acoustic energy into thermal energy to facilitate heat pumping in the process.

Nevertheless, it should be noted that the efficiency of this process is relatively low compared to traditional refrigeration processes. It is attributed to factors such as acoustic damping, heat leakage, and other inefficiencies of the system.

The variation of temperature at the hot and cold ends of the system over time was analyzed to evaluate performance.

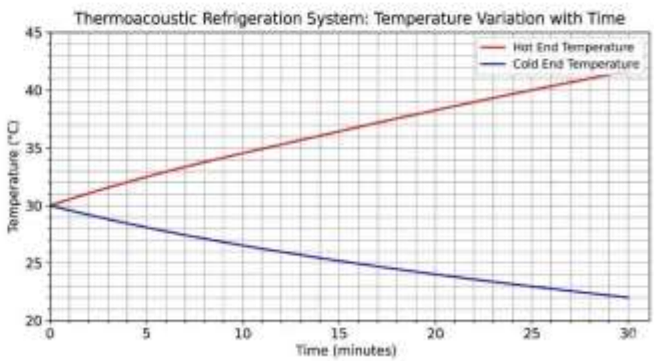

Fig -5: Temperature vs Time Graph

Fig. 5 clearly shows an increase in hot end temperature and a decrease in cold end temperature, confirming thermoacoustic cooling.

6. CONCLUSION

Through the experiment, it is confirmed that thermoacoustic refrigeration is indeed capable of achieving its cooling effects through the use of acoustic waves, and no conventional refrigerants are needed. Indeed, a temperature gradient has been seen in which there is a decrease in the temperature at the cold end and increase in temperature at the hot end with respect to time, proving the thermoacoustic effect.

Factors like frequency of operation, stack structure, and working gas all have impacts on how well the system performs. Even though the system has less efficiency compared to other refrigeration systems, the system still holds advantages like environmental safety, easy design, and maintenance-free system.

In conclusion, the research has proven to be effective in showing the sustainability of a new kind of cooling technology.

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